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Cluster Formation and Stream-bed Armouring:

A photogrammetric study

Katherine Grace Heays

Abstract

Clusters are a self organising structures commonly found in natural rivers. They play an important role in river bed dynamics by providing habitat and increasing bed stability. The aim of the present study was to investigate the development of naturally formed cluster microforms from a flattened bed of graded gravel at constant flow rate. The study was laboratory based, and used photogrammetry to observe the behaviour of well graded, cohesionless sediment at flood flow conditions as clusters formed, evolved and disintegrated. Focus was primarily on the cluster formation and sediment movement, and the development of clusters was observed under varying flow rate and grain size distribution.

The study of gravel dynamics using coloured particles, coupled with image analysis, has enabled in-depth observation of sediment transport and cluster development. To assist in the study of cluster dynamics, a new application of photogrammetry was developed. A digital particle tracking (DPT) program was successfully applied to recordings of sediment movement over extended experiment durations, and a cluster identification program was developed to monitor cluster evolution.

Application of the DPT program to recordings of the gravel bed as it was water worked revealed large spatial and temporal variation of sediment transport rates. Image analysis was used to investigate the progression of armouring, and statistical analysis was applied to surface elevation profiles of the water-worked surface sediment to investigate the effects of armouring.

Objective cluster identification was achieved by monitoring the stationary areas of the bed, and designating clusters as areas with stable groups of large particles. This tool was used in combination with DPT to obtain new insights into cluster formation. The complex interactions of clusters with the surrounding bed were studied, and the behavioural trends of cluster formation are presented in this thesis. Surface coverage of clusters on the test section increased over time, with a maximum surface coverage of around 34% observed between all experiments. Particle shape plays a role in cluster formation, where elongate stones form more stable clusters. Clustering is enhanced by the presence of a stationary object on the bed, and the presence of clusters plays a role in attenuating the sediment transport of the surrounding bed.
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List of Symbols

\( \tau_o \) = shear stress

\( \tau^* \) = grain shear stress

\( \tau^{cr} \) = critical shear stress

\( \tau'' \) = bedform shear stress

\( \tau^{cr*} \) = reference dimensionless shear stress for the median size fraction

\( W^* \) = dimensionless sediment transport number

\( \eta_* \) = relative tractive force

\( R \) = resultant force

\( F \) = hydrodynamic force

\( G \) = gravity force

\( \Theta \) = angle of resultant force

\( \psi \) = angle of friction (angle of repose)

\( f \) = friction coefficient

\( F_D \) = horizontal drag force

\( F_L \) = vertical lift force

\( \rho \) = density of water (kg/m\(^3\))

\( \rho_s \) = density of sediment (kg/m\(^3\))

\( \beta \) = generic constant

\( \alpha \) = generic exponent

\( C_D \) = drag coefficient

\( D_{50} \) = median grain diameter

\( D_{50max} \) = maximum theoretical median grain size of an armoured bed

\( D_{98} \) = grain size diameter where 98% of the sample is finer

\( D_{10} \) = grain size diameter where 10% of the sample is finer
\[ D_i = \text{grain diameter of a particular size fraction} \]
\[ F_i = \text{Fraction of sediment of size } i \text{ available on the surface} \]
\[ u = \text{velocity} \]
\[ u^* = \text{shear velocity} \]
\[ \mu_s = \text{dimensionless bedform parameter} \]
\[ s_s = \text{sediment specific gravity} \]
\[ \theta = \text{Shields’ mobility parameter} \]
\[ \theta_c = \text{critical Shields’ mobility parameter} \]
\[ \theta_{ca} = \text{entrainment threshold for the armoured bed} \]
\[ g = \text{force due to gravity} \]
\[ S_{eq} = \text{equilibrium water slope} \]
\[ R^* = \text{shear Reynolds number} \]
\[ R_p = \text{particle Reynolds number} \]
\[ h = \text{water depth} \]
\[ w = \text{channel width} \]
\[ l_c = \text{cluster length} \]
\[ h_c = \text{cluster height} \]
\[ w_c = \text{cluster width} \]
\[ \lambda_x = \text{streamwise cluster spacing} \]
\[ \lambda_y = \text{streamwise cluster spacing} \]
\[ a = \text{major axis of a particle} \]
\[ b = \text{intermediate axis of a particle} \]
\[ c = \text{minor axis of a particle} \]
\[ A = \text{Area of a particle (plan view)} \]
\[ SF = \text{shape factor} \]
\[ e_i = \text{areal sediment entrainment rate} \]
\[ I = \text{image} \]
\[ x = \text{x coordinate} \]
\[ y = \text{y coordinate} \]
\[ e = \text{entrained} \]
\[ d = \text{deposited} \]
\[ \forall = \text{volume} \]
Chapter 1. Introduction

Rivers, with their abundant resources, water supply, fertile flood plains and source of food have been attractive places for settlement throughout history. Rivers however, are dynamic in nature, and will shift course, widen or deepen in response to their environment, flow and sediment supply. In turn, the river that is a life line to a community, can also damage it through flooding, sediment deposition and erosion. In response to this issue, the dynamics of alluvial deposits have been studied in depth over the last century (Comiti et al. 2005; Yalin 1977). River erosion is a major issue in developed areas, particularly as it increases due to changes to the river catchment, dredging, mining, channelisation, damming and the addition of groynes to the river banks (Frings et al. 2009; Martín-Vide and Andreatta 2008). The role of the engineer is to mitigate these impacts on the community, and therefore the mechanics of sediment transport is of great importance. With knowledge of the behaviour of sediment transport, it is possible to predict the behaviour of the river and therefore improve the application of engineering solutions to rivers undergoing erosion.

Gravel bed rivers contain complicated and dynamic bed topography. The interaction between the water column and moveable sediment on the river bed produces complicated formations termed bedforms. Structures that form on the particle scale are termed microforms, these occur due to the interlocking of particles, near-bed flow characteristics, sediment availability, bed slope and sediment transport conditions (Brayshaw et al. 1983; Laronne and Carson 1976). The complexity that these microforms add to the riverbed makes the prediction of general equations to describe sediment transport and flow conditions even more difficult (Best 1996; Petit 1994)

1.1. Definition of a Cluster

Cluster formations are a particular type of microform, and are characterised by the deposition of bed material into a specifically structured group that is more stable than the surrounding bed (Wittenberg et al. 2007). The term ‘cluster’ describes the formation of an elevated group of bed particles which is generally structured where smaller particles accumulate around a larger, central stone (Brayshaw 1984). There are various definitions for clusters, the broadest being ‘a discrete, organized grouping of particles that sits above the average elevation of the surrounding bed surface’ (Strom and Papanicolaou 2008). Clusters are often characterised by
having a larger stone providing support to smaller stones, therefore creating a group of particles more stable than the surrounding bed. Figure 1-1 shows a stylised cross-sectional view of a typical cluster microform.

![Figure 1-1 Typical cluster microform](image)

**1.2. The Role of Clusters in the Natural Environment**

In beds with coarse, graded sediments, an armouring effect tends to occur when the bed is water worked. The term ‘armouring’ describes selective entrainment of smaller particles which eventually leaves a surface layer of gravels of a generally larger size than that of the underlying bed (Chin 1985). This layer works to protect the bed underneath from erosion as the larger particles take higher flows to entrain, therefore raising the shear stresses needed to entrain any particles on the bed. Observations of particles in the armour layer have revealed that the particles tend to congregate into groups of particles with a common structure (Chin 1985). These clusters form a part of the fundamental physical process behind the natural response of the river bed to mitigate erosion.

The occurrence of clusters in natural streams is widespread, for example a New Zealand survey of 12 headwater streams found their presence in all streams, occupying up to 4.4% of the surface area (Biggs et al. 1997a). In addition to providing stability to the river bed in flood, clusters provide a more stable habitat to river life. During flood events the habitat of river life such as periphyton, insects and fish can be destroyed. As clusters are more stable than featureless bed gravel, they can remain intact during the peak flows in floods, and have been observed to remain on the bed for greater than one year. The permanence of clusters allows them to provide refuge for aquatic life during flood. Clusters also improve river biodiversity by providing a range in hydraulic conditions, and increase in surface area for invertebrates and periphyton to occupy (Biggs et al. 1997b).
1.3. State of Research so far

While investigation into sediment transport and fluid mechanics has a long history, research into clusters began in the mid 1980’s. Brayshaw (1984)’s documentation of clusters in a number of rivers instigated an effort to explore the phenomenon further.

Both field surveys and laboratory experiments have been carried out over the last decade in an effort to elaborate on the picture first presented by Brayshaw (1984). Generally speaking, there are limitations to the amount of research that is practical to be conducted in field situations using current techniques and technology. Cluster formation and disintegration generally occurs only in high flow conditions, which makes observation difficult due to the turbidity of the water, and presents possible dangers associated with the rapid flow rates (Strom and Papanicolaou 2002a; Wittenberg et al. 2007). This has resulted in field studies simply using a method of tagging cluster particles and surveying their formations before and after flow events (Strom and Papanicolaou 2002a). The resulting work has provided a register of the frequency of clusters in various streams.

Laboratory research allows more control of the experiment and consequently more in depth studies can be conducted, however this introduces issues regarding scaling and flow formations when comparing to natural conditions (Wittenberg et al. 2007). To enable strict control of the sediment properties, glass and Teflon spheres have been used in the majority of laboratory cluster experiments (Papanicolaou and Kramer 2006; Papanicolaou and Schuyler 2003; Papanicolaou et al. 2003; Strom and Papanicolaou 2002b; Strom et al. 2004; Strom and Papanicolaou 2006). This enables the specific gravity, particle availability, spacing and shape to be easily controlled and experiments are easily repeatable. These experiments dominate the studies that have been conducted on clusters, with only a handful of studies investigating the behaviour of clusters using natural, graded gravels.

Advances in technology have assisted the trend toward more intensive study of bedforms in order to study processes instead of form (Wittenberg et al. 2007). Photogrammetry and laser velocimeters have been significant tools in recent studies, enabling accurate, unobtrusive information to be recorded (Schuyler and Papanicolaou 2000; Strom and Papanicolaou 2002b; Strom and Papanicolaou 2008). Colouring has also been used to differentiate between sediment particles with different properties and this has advanced unobtrusive particle
Chapter 1. Introduction

identification further (Billi 1988; Schuyler and Papanicolaou 2000; Strom and Papanicolaou 2002b).

1.4. Objectives

The aim of this study was to investigate the topographical processes of a gravel river bed as cluster formations developed under constant flow conditions.

1. Develop a process to identify and measure the development of clusters using a novel application of photogrammetry

2. Quantify the physical properties of clusters as they form on the bed surface under varying sediment and flow conditions

3. Explain the self organizing nature of cluster formations by exploring their origin and relationship with the surrounding bed

In addition to these three main objectives, this thesis also explores the sediment transport behaviour of the bed and the armouring that occurs. Both of these subjects heavily influence cluster formation and needed to be understood before an understanding of cluster formation could be reached.
Chapter 2. Literature Review

Clusters are organised groupings of particles that lie above the plane of the bed. To be classified as a cluster, there must be a minimum of two particles in the group (Strom et al. 2004). Clusters differ to larger bed formations such as step pools and riffle pools, as they are generally formed on the particle scale, creating formations such as cellular and pebble structures (Strom and Papanicolaou 2002a; Strom et al. 2004). This report will focus on cluster formations.

Cluster microforms are common in gravel-bed rivers. Pebble clusters have been found to be the most common small scale bedform in a range of fluvial environments (Wittenberg et al. 2007). Clusters influence and are affected by the interaction of the flow structure, entrainable sediment and stable bed morphology (Strom and Papanicolaou 2002a; Strom et al. 2004). They play an important role in gravel-bed river dynamics, affecting bed stability, bedload transport rates, downstream particle movement, overall flow resistance and local flow field characteristics (Strom and Papanicolaou 2008). It is generally accepted that clusters improve bed stability (Brayshaw 1984; Papanicolaou and Schuyler 2003; Reid et al. 1992; Strom and Papanicolaou 2002a; Strom et al. 2004), despite a few claims to the contrary (Billi 1988).

Increased knowledge of clusters is essential for the understanding of sediment transport behaviour, the monitoring and protection of aquatic life (Biggs et al. 1997a; Biggs et al. 1997b) and has also been useful for the study of palaeocurrents (Cin 1968). The presence of clusters can improve biological diversity through the improvement of morphological diversity which provides a wider range of habitat for benthos populations (Biggs et al. 1997a; Strom and Papanicolaou 2002a). They also have the effect of improving water quality through reduced suspended sediment once cluster formations have been established (Papanicolaou and Schuyler 2003).

2.1. Background Theory

Knowledge of sediment transport processes is important for investigating and modelling the processes and characteristics of a stream channel. Sediment transport can occur as erosion, accretion or general bed motion. It is generally acknowledged that a significant contributing factor for the development of cluster microforms on a river bed is the condition of selective transport (Reid et al. 1992). Cluster formation has been seen to occur under conditions of
uniform grain size, however this has generally been under entirely artificial conditions (Papanicolaou and Schuyler 2003). The entrainment and deposition of the bedload is ultimately the formative process that produces clusters. Because of this, an understanding of the fundamentals of sediment transport, and the interaction between the solid bed and fluid water column is necessary.

2.1.1. Sediment Entrainment

The initial entrainment of a particle is usually a result of peak Reynolds stresses in the local flow field, which are generally linked with organised fluid motion in the form of ejections and sweeps, with sweeps being the most efficient at entrainment (Best 1993; Nino and Musalem 2000). Sediment entrainment is governed primarily by the size and weight of the particle, with smaller lighter particles entraining more readily than larger heavier ones. Knowledge of sediment transport rates is important for determining the bed load transport rate of rivers. Generalised formulae for the quantification of sediment transported from a bed have been developed over the past two centuries. Du Boys (1879), Meyer-Peter and Muller (1948) and Einstein (1942) first proposed some of the concepts which are still frequently used today. Since then, numerous sediment transport equations have been proposed, however they tend to be condition specific. Various definitions of incipient motion exist, and include: extrapolation of bedload transport rates to either zero or a low reference value, visual observation, development of competence functions that relate shear stress to the largest mobile grain size from which one can establish the critical shear stress for a given size of interest, and theoretical calculation (Buffington and Montgomery 1997).

Particle entrainment can be considered on both the bed scale and the particle scale. When observing movement on the particle scale, it is important to consider the turbulence characteristics of the flow. Many entrainment formulae use time averaged flow information to estimate the critical entrainment velocities for a particle. While this approach is simpler, it is limited, as turbulence bursts increase instantaneous drag forces on a particle by up to four times the ordinary level, and entrainment is also dependent on the duration of these fluctuations (Paiement-Paradis et al. 2010). It has been established that turbulence plays a major role in particle entrainment, and in their study, Paiement-Paradis et al (2010) found that fluid acceleration played a more important role than Reynolds shear stress or normal stresses for bedload movement but there is still uncertainty over which aspect of turbulence plays the primary role in entrainment (Paiement-Paradis et al. 2010).
2.1.2. Initial Entrainment of Uniform Sediment

River bed sediment can be divided into cohesive and non cohesive types. Cohesive sediment has a resistance force proportional to the weight of the particle combined with the strength of the cohesive bond. Non cohesive sediment has a resistive force proportional to the weight of the particle alone (Raudkivi 1967). A cohesionless plane bed of stationary, uniform gravel particles will remain stationary until the hydrodynamic forces of the surrounding flow reach a certain level. At this level, some of the particles in the cohesionless bed will begin to move, this point of initial movement is called the ‘critical condition’ or ‘incipient condition’ (Graf 1971). Not all particles in the surface layer of the bed will entrain at the same time, this is due to the turbulent nature of the flow, and the resulting fluctuations of hydrodynamic forces (Graf 1971). Entrainment of non-cohesive sediment will occur whenever the surface shear stress ($\tau_o$) acting on a particle is greater than the forces holding that particle in place. The value for the shear stress at which entrainment will take place is called the critical shear stress, and is denoted as $\tau_{cr}$ and the condition where entrainment will occur can be described by the ratio

$$\eta_s = \frac{\tau_o}{\tau_{cr}} > 1$$

(1)

where $\eta_s$ is referred to as the “relative tractive force”. Only the surface grains will be exposed to the tractive force, therefore, only those grains will be entrained.

To enable description of the entrainment of an individual, stationary grain in a plane, cohesionless uniform bed, a diagram of the relevant forces is useful (Figure 2-1). Entrainment of the particle is dependent on the magnitude of the vector $R$, where $R$ is the resultant of forces $F$, the hydrodynamic force, and $G$, the gravity force (Yalin 1977).

$$R = F + G$$

(2)

The weight force on the particle stays constant, however the hydrodynamic force changes with velocity. The hydrodynamic force is comprised of the lift and drag forces generated by the flow. These forces are both functions of the same variables so can be grouped into one vector in this instance. In the case of fully turbulent flow the angle of this vector ($\Theta$) does not vary with Reynolds number. At low flow rates, the particle is fully at rest, and is in contact with the surrounding grains. Reaction forces at point A and B keep the particle stable, this occurs when $R$ is positioned between points A and B. As the flow increases, $R$ changes
magnitude and position. When $R$ is above $B$, there is no longer a reaction force at $A$, and the only point of support for the grain is against the downstream neighbouring particle $B$. As the flow increases further, the vector $R$ rotates upwards, with entrainment occurring once the angle between the vector, $R$, and the horizontal is greater than the angle of friction ($\psi$). Hence, at the critical condition (Yalin 1977):

$$ f = \tan(\psi) \quad (3) $$

where $f$ = the friction coefficient and $\psi$ = the friction angle (angle of repose) between the grains.

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Forces acting on a particle by the fluid are the horizontal drag force \((F_D)\) and vertical lift force \((F_L)\). The drag force consists of skin friction force and the pressure difference between the upstream and downstream sides of the particle created by flow separation downstream of the particle. Elementary theory (Raudkivi 1998) of drag states,

\[
F_D = \frac{1}{2} \rho C_D \pi \frac{D}{4} u^2 \tag{4}
\]

where \(u\) is the near-bed velocity, \(D_{50}\) is the grain diameter, and \(C_D\) is the drag coefficient. The lift force is also created by the flow, partially due to the curvature of the streamlines over the particle, and partially due to flow separation. The lift force is given by a similar equation to \(F_D\), allowing the two to combine into one driving force equation

\[
F_D = \frac{1}{2} \rho C_D \pi D_{50}^2 (\alpha u^*)^2 \tag{5}
\]

where \(C_D\) and \(\alpha\) are non-dimensional coefficients and \(u^*\) is the shear velocity due to the skin friction of the particle. \(u^*\) is defined as \(u^* = (gyS_{eq})^{0.5}\), where \(y\) is the water depth and \(S_{eq}\) is the slope of the water surface. \(\alpha u^*\) is the flow velocity at a distance equal to the order of magnitude of \(D_{50}\) from the bed.

The stabilising force of the particle is described by the equation

\[
F_s = \rho g (s - 1) \frac{\pi}{6} D_{50}^3 \mu_s \tag{6}
\]

where \(\mu_s\) is a factor accounting for the bedform and \(s\) is the specific gravity of the particle. Provided \(F_s > F_D\), the particle will remain stationary, this provides a basis for determining a critical entrainment velocity, i.e. \(F_s = F_D\):

\[
\frac{1}{2} \rho C_D \pi \frac{D}{4} u^2 (\alpha u^*)^2 = \rho g (s - 1) \frac{\pi}{6} D_{50}^3 \mu_s \tag{7}
\]

which can be rearranged to

\[
\theta = \frac{u^*}{(s-1)gD_{50}} = \frac{\mu_s}{c_D 3\alpha^2} \tag{8}
\]

where the LHS is the Shields’ parameter.

Shields et al. (1936) developed a relationship to determine the threshold of motion of sediment particles where \(\theta\) and \(\theta_c\) are the actual and critical Shields’ mobility parameters. The critical Shields stress may be calculated using Shields diagram (Figure 2-2), where Shields et
al. (1936) determined the point of zero transport rate for various sediments through extrapolation of his experimental work (Shields et al. 1936). The shear velocity, $u^*$, and shear Reynolds number, $R^* = u^* D_{50}/v$ (where $v$ is the viscosity of water) are required for the use of this graph. The shear velocity can also be calculated using the velocity profile of the water column and the law of the wall based on the von Karman-Prandtl equation (Bradshaw 1971):

$$\frac{u}{u^*} = \frac{1}{K} \ln \left( \frac{h}{h'} \right)$$

(9)

where $K$ is a constant = 0.41, $h$ is the water depth, and $h'$ is the depth at which the flow velocity theoretically reaches zero according to the law of the wall.

Sheilds parameter was developed by observation of the behaviour of virtually uniform sediment. The particles, which ranged from 0.36 to 3.44 in diameter, were observed in the early stages of flow before bedforms have a chance to develop. When $R^*$ is greater than 500, $\tau^*_{cr}$ approaches a constant (0.06). However, values significantly less than this have been observed in subsequent experiments (Andrews 1983; Carson and Griffiths 1985).
2.1.3. Initial Entrainment of Graded Sediment

Determination of the entrainment threshold is an important but difficult task. The $\tau_{cr}^*$ of graded gravel beds is much more complicated than that for uniform gravels. Generally, the Shields parameter; or the dimensionless critical shear stress, is used as a description of threshold entrainment. However this only provides an indication of what the stress might be, and authors subsequent to Shields have proposed a number of amendments to his equation, particularly when applied to graded, gravel-bed rivers (Andrews 1983; Buffington 1999; Buffington and Montgomery 1997; Petit 1994). Investigation into the entrainment of graded gravels has shown that while smaller particles have less mass, the larger particles have a lower critical threshold due to their exposure (Andrews 1983; Mao and Surian 2010; Petit 1994). Sediment hiding and protrusion effects complicate the entrainment of particles and as a result, entrainment of particles is not only related to their absolute size, but also their relative size (Andrews 1983; Ashworth and Ferguson 1989; Mao and Surian 2010; Parker 1990; Petit 1994; Wilcock and Crowe 2003).

Andrews (1983) proposed an alternative method for determining the critical shear stress which takes into account the individual particle size relative to the average grain size. This was developed by observation of critical entrainment stresses of several naturally sorted gravel and cobble beds. It was found that for bed particles 0.4 to 4.2 times the median diameter of the subsurface bed material, $D_{50}$, the average critical dimensionless shear stress $\tau_{cr}^*$ is given by

$$\tau_{cr}^* = 0.0834 \left( \frac{D_i}{D_{50}} \right)^{-0.872}$$  \hspace{1cm} (10)

where $D_i$ is the particle size of a particular size fraction. For bed particles larger than $4.2D_{50}$, the $\tau_{cr}^*$ appeared to approach a constant value of 0.02 (Andrews 1983). In review of Andrews (1983) work combined with experiments of his own, Petit (1994) proposed two modified versions of this equation. The first equation is for the threshold of initial movement, where Petit (1994) proposed the following equation:

$$\tau_{cr}^* = \alpha \left( \frac{D_i}{D_{50}} \right)^\beta$$  \hspace{1cm} (11)

$\alpha$ should be equal to 0.05 and $\beta = -0.7$. In his second equation, for generalised movement, Petit (1994) proposed $\alpha = 0.068$ and $\beta = -0.8$. Generally equations presented in this form
suggest a number close to the dimensionless shear stress for the reference grain size when
determining the coefficient $\alpha$, and $\beta$ ranges between 0, which signifies fully selective
transport, and $-1$, signifying equal mobility of all grain sizes (Gob et al. 2010; Parker et al.
1982a)

2.1.4. Generalised Motion of Sediment

The interplay between sediment supply, armour layer development and bed load transport is
very complex. The movement of grains in sediment transport is discontinuous, with some
grains remaining stationary and others saltating, rolling or being entrained and deposited
downstream. The surface coarsening and development of coherent structures that make up the
armour layer reinforces the stability of the surface layer (Brayshaw et al. 1983; Hassan and
Church 2000). While much progress has been made in the development of a ‘general
equation’ to describe sediment transport, a complete equation still remains elusive, (Diplas
and Shaheen 2007).

It has been established that the bed load composition is proportional to the grain size
distribution of the surface sediment (Wilcock and McArdell 1993). Considering this and
incorporating and extending work from other authors (Parker 1990; Proffitt and Sutherland
1983), Wilcock and Crowe (2003) proposed a sediment transport equation. Their equation
considers individual size fractions of the bed including the sand fraction, and includes a
hiding function which takes into account the relative size of a particle and the effect this will
have on its critical shear stress. Their equation estimates the mass of entrained sediment for
each fraction of the bed in terms of the dimensionless transport of fraction $i$ ($W_i^*$).
Application of their fractional transport equation requires knowledge of the surface sediment
size distribution and the shear stress ($\tau_0$). The equation first of all requires the determination
of a reference shear stress for the entrainment of the median size fraction ($\tau_{rm}$), which
represents the shear stress at which a small quantity of the sediment fraction is entrained ($W_{rm}^*$
$= 0.002$). This value can be calculated using the following equation

$$\tau_{rm} = \tau_{rm}^*(s - 1)\rho g D_{sm}$$  \hspace{1cm} (12)

where $\tau_{rm}^*$is the reference dimensionless Shields stress for mean size of the bed surface ($D_{sm}$).
$\tau_{rm}^*$can be derived using

$$\tau_{rm}^* = 0.021 + 0.15e^{-20F_s}$$  \hspace{1cm} (13)
where \( F_s \) = the surface fraction of sand. This value can then be used to determine the reference shear stress for the entrainment of the particular size fraction (\( \tau_{ri} \))

\[
\tau_{ri} = \tau_{rm} \left( \frac{D_i}{D_{sm}} \right)^b
\]

(14)

where \( D_i \) is the grain size of the particular size fraction and \( b \) is an empirically derived exponent, where \( b = 0.12 \) when \( D_i/D_{sm} < 1 \) and \( b = 0.67 \) when \( D_i/D_{sm} > 1 \). \( \tau_{ri} \) can then be used in conjunction with \( \tau_0 \) to find the ratio of shear stress to the reference shear stress (\( \Phi \)), which can then be used in Equation 15 to determine \( W^*_i \)

\[
W^*_i = \begin{cases} 
0.002\Phi & \text{if } \Phi < 1.35 \\
0.894^{1.5} & \text{if } \Phi \geq 1.35 
\end{cases}
\]

(15)

\( W^*_i \) is related to the fractional sediment transport rate by Equation 16

\[
W^*_i = \frac{(s-1)q_{bi}}{F_i u^3}
\]

(16)

where \( q_{bi} \) = the volumetric transport rate per unit width of size \( i \) and \( F_i \) = the proportion of size \( i \) on the bed surface.

2.1.5. Shear Stress

Shear stress (\( \tau_0 \)) can be divided into two areas, the grain shear stress (\( \tau^* \)) which is due to the resistance of individual particles, and the bedform shear stress (\( \tau^{''} \)), which is additional shear stress due to the form of the river, and includes, for example, hiding and protrusion effects, pool, and riffle sequences (Petit et al. 2005). Calculation of bed mobilisation and transport should only use the grain shear stress (\( \tau^* \))

Bedform shear stress (\( \tau^{''} \)) is the shear stress required to destroy the bedform, which takes into account hiding and protrusion effects, pool and riffle sequences and will have an influence on the stream power required to initiate bedload motion in a river (Petit et al. 2005). The bedform shear stress is defined as the ratio between the grain shear stress (\( \tau^* \)) and the total shear stress (\( \tau_0 \)). Petit et al. (2005) investigated this ratio in a number of small, medium and large rivers with catchments within the range of less than 20 km\(^2\), 40 to 500 km\(^2\) and greater than 500 km\(^2\), respectively. Small rivers were found to have \( \frac{\tau^{''}}{\tau_0} < 0.3 \), medium rivers had
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0.4 < \frac{\tau'}{\tau_o} < 0.5, and the largest river had \frac{\tau'}{\tau_o} > 0.7. This indicates that bedforms have the most significant effect on the smaller rivers.

Shear stress can be calculated using a variety of different methods. Different calculation methods will yield different shear stress measurements (Rowinski et al. 2005). Wilcock and Crowe (2003) criticise the tendency to use the substrate sediment grading as the reference grain size due to the superficial nature of sediment transport, and blame the condition specificity of other formulae on this oversight (Wilcock and Crowe 2003). Buffington and Montgomery (1997) found that variations in the critical entrainment threshold for the \( D_{50} \) of a gravel bed river stem from differences between the authors’ definition of incipient motion, choice of surface, subsurface or laboratory mixture median grain size, relative roughness, and flow regime.
2.2. Armouring

In a graded river, the erosive power of water will selectively transport fine grains leaving a layer of coarser particles termed an ‘armour layer’ (Chin 1985; Parker et al. 1982b). Fluid motion in the boundary layer near a granular bed causes the entrainment of finer sediment. This process generally occurs in ejections and sweeps and the selective entrainment of fines results in a more heterogeneous sediment size in the top layer of the bed, usually one or two grains thick (Chin 1985; Nino and Musalem 2000).

Armour layer roughness determines flow properties such as the mean flow velocity, turbulence, and sediment transport (Aberle and Nikora 2006). Energy losses which occur due to bed roughness can be divided into two categories; smaller scale particle roughness, and larger scale form roughness. Particle losses are dependent on particle size, shape and arrangement and are due to viscous drag on the bed surface and form drag due to small scale roughness elements (Aberle and Nikora 2006). Form roughness losses occur due to large-scale bed forms and associated drag.

2.2.1. Particle Behaviour

Observation of a relatively coarse particle on a finer bed shows that if the size of coarse particles exceeds a critical value, the down flow ahead of the particle will cause a local scour hole around the front perimeter of the particle. The particle slides forward incrementally into the hole, gradually reducing its exposure and changing its angle of repose, $\psi$. As the relative size of the particle decreases, so too does the tendency for the particle to embed. With this trend the particle will also move more erratically and $\psi$ will reduce (Chin 1985).

The behaviour of an individual particle $i$, amongst others can be imagined by considering the applied bed shear stress $\tau_o$, the minimum stress required to move an individual particle $\tau^*$, and the critical shear stress of the whole bed material is $\tau_{cr}^*$. The behaviour of the particle under various shear stresses can be identified:

- $\tau^* > \tau_{cr}^* > \tau_o$ and $\tau_{cr}^* > \tau^* > \tau_o$: No grains move
- $\tau_o > \tau_{cr}^* > \tau^*$ and $\tau_o > \tau^* > \tau_{cr}^*$: All grains move
- $\tau^* > \tau_o > \tau_{cr}^*$: The bed material moves but the overlying exposed grain, $i$, does not and becomes embedded
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\( \tau_{cr}^* > \tau_o > \tau^* \)

The exposed particle overpasses the bed surface which itself remains undisturbed. Larger grains roll and slide over a bed of small grains, whereas a bed of small particles may saltate.

On an individual scale particle behaviour can be erratic, but the nature of the armoured bed is to act as a unified surface. The stability of individual particles is dependent on the stability of the surrounding bed therefore the study of armouring is conducted in terms of the surface layer.

2.2.2. Development of Armoured Beds

The development of an armoured bed is time dependent, and once formed, will be characterised by the local flow characteristics. Armouring will only occur if the shear stress acting on the bed is within a range that is high enough so that transport occurs, but not so high that the bed is in full motion and all surface particles are entrained. Two types of armoured condition occur:

1. Static armour is the case where selective transport removes finer grains and leaves a surface of coarse material on the bed. During formation of the armour, the rate of entrainment exceeds the rate of sediment supply, and is generally confined to the case where no sediment supply is available. The bed degrades until the armour layer is fully formed, at which stage no more entrainment occurs and the bed is in ‘static equilibrium’ (Chin 1985; Hunziker and Jaeggi 2002). Static armour occurs at flows between the critical entrainment threshold for the bed (\( \theta_c \)) and the entrainment threshold for the armoured bed, (\( \theta_{ea} \)) and can be described as: \( \theta_c < \theta < \theta_{ea} \) (Chin 1985; Hunziker and Jaeggi 2002; Jain 1990). In between these two thresholds the eroded material is finer than the sub surface material, therefore the surface gradually coarsens over time and the availability of fines decreases and the availability of coarse particles increases. When equilibrium is reached, the quantity of eroded material is zero. At shear stresses that exceed the entrainment threshold for the armoured bed, if no sediment supply is available, when equilibrium is reached, the eroded material is the same as the parent bed material.
2. Mobile armour occurs when the armour layer is subject to stresses higher than the critical value for the armour layer to disintegrate, but with a sediment supply, the rate of entrainment equals the rate of replenishment, therefore allowing the armour to remain in ‘mobile equilibrium’. This occurs when $\theta_{ca} < \theta < 0.11$ (Hunziker and Jaeggi 2002). At equilibrium the composition of the eroded material will equal that of the bed material (Parker et al. 1982a), during the evolution toward equilibrium, the eroded material will be finer than the sub surface material, and coarsen over time until equal mobility is reached (Jain 1990). At rates higher than $\theta = 0.11$, the bed is fully mobile and no armour layer will form (Hunziker and Jaeggi 2002).

The formation of the armour layer begins with dune development. As fines are entrained and deposited they form bed features, the size and shape of which are dependent on the flow however the presence of graded material limits their development (Parker et al. 1982a; Parker et al. 1982b). When no sediment supply is available, this phase can be very short and is followed closely by the emergence of a coarse surface layer punctuated by cluster formations (Chin 1985). Small and medium sized particles group around the larger stones forming clusters that are apparently more stable than the surrounding bed. Entrainment of the finer fractions of the bed exposes more large particles around which clusters can form. As this process continues the availability of smaller particles decreases, therefore limiting the potential for new clusters to form and the bed nears the equilibrium condition (Chin 1985).

### 2.2.3. Equations Describing Armouring

A definition of the critical value for the armour layer to disintegrate has been investigated through theoretical and experimental analysis. Chin (1985) gave an approximation of the critical threshold of the armour layer in the equation:

$$\theta_{ca} = \theta_c \left( 0.4 \left( \frac{D_{50max}}{D_{50}} \right)^{-0.5} + 0.6 \right)^2$$  \hspace{1cm} (17)

Where $\theta_c = 0.05$ using Sheild’s entrainment function for hydraulically rough conditions. $D_{50max}$ is the maximum theoretical average grain size of the armoured bed, and can be determined using the experimental limiting values of Chin (1985)

$$D_{50max} = \frac{D_{max}}{1.8}$$  \hspace{1cm} (18)
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Following on from this, equations that describe the bed degradation and change in grain size distribution of the armour layer as it progresses toward equilibrium have also been developed (Parker and Sutherland 1990; Sieben 1999).
2.3. Cluster Structure and Different Types of Clusters

Many cluster structures have been identified in the field. The broad description of a cluster presented by Brayshaw (1984) can be divided into the different arrangements that the particles create. A description of the various types of cluster shapes observable was first presented by Strom et al. (2005) and subsequently modified by Hendrick et al (2010).

2.3.1. Different Types of Cluster Shape

Observation of cluster formations in a study of two rivers over a period of 3 years found that clusters could be categorised into five shapes; the pebble cluster, line, comet, ring, and heap (Figure 2-3) (Strom et al. 2005). The term pebble cluster is used to describe the traditional cluster formation, consisting of one anchor stone supporting smaller particles upstream (stoss) and downstream (wake). While the pebble cluster formation is the most common, four other shapes, the line, comet, ring and heap clusters, were also identified in the stream survey (Strom et al. 2005). Line clusters lack any defined stoss or wake region, and are more uniform in sizing of constituent particles. They are generally oriented in a straight line parallel to the direction of the flow. Comet clusters form a wider arrangement, with large pebbles upstream, two tails of medium sized particles on either side of the headstones and an area of finer particles in the middle of the arrangement. Ring clusters are the least common, and consist of an outer ring of larger pebbles surrounding smaller sediment. Heap clusters can have several particles stacked on top of each other, and are the largest noted formation in terms of volume (Strom 2006; Strom and Papanicolaou 2008; Strom et al. 2005).

![Figure 2-3 Different cluster types (Strom et al. 2005)](image)

Typical cluster  Line cluster  Comet cluster  Ring cluster  Heap cluster

![Figure 2-4 Additional cluster types (Hendrick et al. 2010)](image)

Upstream Triangle  Downstream Triangle  Transverse Line  Diamond
A later field study conducted by Hendrick et al (2010) comparing the morphologies of clusters observed in nature to those observed in previous studies and in the lab found that the cluster shapes aligned well to those predicted (Hendrick et al. 2010). Tagging and photographic monitoring of clusters in two sections of a river over 1.5 years and 4 major flood events allowed good observation of the natural evolution of clusters. The typical shaped cluster, with one or more anchor stones and smaller stones on either side of the anchor, was found to be the most stable, likely due to its streamlined shape.

Additional cluster shapes were identified by Hendrick et al. (2010) in their field survey (Figure 2-4). A simple upstream triangle-shaped cluster was the most common type of cluster, and was observed to be the most likely shape for a new cluster to form into, eventually comprising 77% of all clusters. The more complex cluster shapes such as the ring, diamond and line were less common and transverse-line and downstream-triangle shapes made up <5% of the cluster population. A note was taken of the presence of two particle clusters, and their abundance suggested that they are a common precursor to a proper cluster (Hendrick et al. 2010).

2.3.2. Typical Cluster Structure

The most commonly researched type of cluster, the typical cluster, also referred to as the pebble cluster, was the first type of cluster to be identified and studied; it has attracted the most amount of research, and is what is meant herein when referring to a ‘cluster’ unless specified otherwise. Typical cluster formations comprise three distinct sections; the obstacle, stoss and wake (Figure 2-5). The anchor stone (or obstacle) is an unusually large particle that is deposited on the river bed. This provides an anchor for the cluster and initiates cluster formation (Brayshaw 1984). The anchor stone is usually in the D98 to D99 fraction of the bed gravel (Brayshaw 1984) but has also been reported to be in the top D85 (Papanicolaou et al. 2003). The presence of the larger particle in the flow field affects the local hydrodynamic forces in the water, stimulating the arrangement of surrounding particles into depositing either upstream or downstream of the anchor stone depending on their size (Brayshaw et al. 1983). Figure 2-6 depicts the pressure field surrounding a hemispherical particle when it is subjected to flow. The high pressure zone upstream of the particle is caused by the downward deflection of flow (Melville and Raudkivi 1977). Acceleration of flow around the sides of the particle creates a low pressure zone where particles are unlikely to come to rest due to high
shear stress. Downstream of the particle, the wake creates a low pressure zone in response to the free stream separating from the recirculation zone behind the particle (Brayshaw et al. 1983).

The area upstream of the anchor stone is referred to as the stoss, and usually contains particles of medium size, within the range of $D_{74}$ to $D_{94}$ (Brayshaw 1984). The stoss is a relatively stable zone, and is less likely to disintegrate than the wake (Billi 1988). The formation mechanics of the stoss has been proposed to occur in two different ways, the first process, as described by Brayshaw et al. (1983), and Chin (1985) involves the following steps: The presence of the anchor stone in the flow field causes a downward deflection of the flow, and a corresponding rise in pressure. This causes the finer sediment in front of the anchor stone to be removed, leaving a scour hole. The larger, more stable particles are left on the surface of the scour hole, it is these particles which form the stoss region. The anchor stone slides into the hole, and is embedded slightly, causing greater stability for the stone (Brayshaw et al. 1983; Chin 1985). The second process for stoss formation as described by Papanicolaou at al. (2003) is a result of deposition of particles from upstream. In this case, the anchor stone acts as a barrier to transportation, and particles in motion come to rest in front of the stone, both creating the cluster, and increasing the size of the barrier to other particles, therefore increasing the likelihood of the cluster growing further (Papanicolaou et al. 2003).

The presence of the larger stone in the flow field creates secondary currents, as the water flowing over the stone separates into a recirculation zone behind the obstacle. This area has a relatively low pressure and finer suspended sediment is drawn into this zone and deposited. This area of accreted sediment is termed the wake, with sediment sizes in the range of $D_8$ to $D_{46}$ (Brayshaw et al. 1983). The wake sediment is the least stable and is prone to re-entrainment and replacement deposition, (Billi 1988). High local boundary shear stresses on either side of the anchor stone mean these areas are unlikely to have particles come to rest (Brayshaw et al. 1983).
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Figure 2-5 Idealised diagram of a cluster microform, showing dimensions used to characterise the cluster from (Brayshaw 1984)

Figure 2-6 Bed pressure coefficients, $C_p = (p-p_0)/0.5p_0u_0^2$ surrounding an isolated stationary hemispherical particle (Brayshaw et al. 1983)

2.3.3. Cellular Structures

The presence of cellular structures were identified in an investigation of the formation of armour layers in a field investigation of Harris Creek in British Columbia, Canada and in laboratory experiments (Church et al. 1998). These ‘cell’ structures developed simultaneously with the armour layer and were subsequently described by Hassan and Church (2000) as cells approximately 1 m in diameter with boarders consisting of pebble to boulder sized material generally larger than the $D_{84}$. Material in the centre of the cell was found to be significantly finer than the material in the boarder (Hassan and Church 2000). The formation of these cells was found to occur in both the field and laboratory experiments, and could therefore be closely observed in the lab. Observations made during a series of flume runs found that the
streambed surface started coarsening at very low flows as fines were entrained. As the flow increased, there was no corresponding increase in surface coarsening, but instead larger particles would roll and come to rest against a static particle of similar size leading to cluster formation. These clusters would then grow into particle lines and eventually into a reticulate structure blanketing the bed surface (Church et al. 1998). These structures significantly stabilized the bed, providing the flow did not exceed twice the Shields’ threshold (Marion et al. 2003). Such formations differ from the clusters typically studied in the literature, and while they are not strictly clusters, their presence may play an important role in the life cycle of clusters.

Figure 2-7 Image showing the appearance of the cellular structures (Hassan and Church 2000)
2.4. The Process of Cluster Formation and Disintegration

2.4.1. Cluster Formation

Clusters are often considered to be formed under selective transport conditions on the waning limb of the flood hydrograph, (Billi 1988; Brayshaw 1984; Reid et al. 1992; Wittenberg and Newson 2005). Typically, observation of cluster dynamics must be performed in the laboratory due to the dangers of measurement in flood conditions. The laboratory investigations conducted by Brayshaw (1984) produced some useful observations on the cluster formation process. In the laboratory at peak flow, the bed was in continuous motion. Only as the flow rate decreased was an anchor stone deposited. This was followed shortly by deposition of fines in the wake, which continued for a period of time, during which no stoss side deposition was observed, and in fact, minor scour occurred upstream of the anchor stone. Stoss particles were deposited at a lower flood stage. The deposition of one or two particles instigated the deposition of more stoss particles, due to the increased size of the cluster creating a greater obstruction for moving particles (Brayshaw 1984).

2.4.2. Cluster Evolution

Observation of the change in cluster shape before and after a flood found that 17 out of 61 original clusters evolved from one shape of cluster to another under the influence of increased flow. The evolution of clusters is difficult to monitor in field conditions, therefore only clusters comprised of spherical glass beads have been continuously observed under increasing shear stress. In these experiments, cluster progression could be described, starting from no cluster, as forming a two particle cluster, then a comet, a triangle, rhomboid then eventually disintegrating (Figure 2-8) (Papanicolaou et al. 2003; Strom and Papanicolaou 2002a). Comparison of this progression with clusters from the field found that while evolution did exist in the field it did not follow that which was predicted by Papanicolaou et al. (2003). However the flow and sediment conditions between the two studies were significantly different, with the lab observations focussed on the cluster throughout a steadily changing hydrograph using glass spheres, and the field observations being taken between major flood events (Hendrick et al. 2010).
Strom and Papanicolaou et al. (2004) classified cluster evolution under increasing flow as occurring in three phases with respect to the flow sediment interaction, Phase I, Phase II, and Phase III. In Phase I, the clusters act as sediment sinks, because passing suspended sediment is trapped in the cluster formation. Phase II is an intermediate stage, where clusters have reached their maximum size, but have not yet started to disintegrate. This stage has no effect on the bedload rate of the river. Phase III is the stage where clusters start to disintegrate. At this stage they become a source of sediment, increasing the mean bedload rate as sediment from the less stable areas of the cluster, such as the wake, is released. Eventually the entire cluster will disintegrate (Strom et al. 2004).

Observation of cluster formation showed that cluster growth occurred primarily when particles rolled down the side of the existing cluster and were entrained into the wake section. No growth was attributed to the deposition of particles into the wake from rolling over the top of the cluster, or from deposition into the stoss indicating lateral movement is primarily in the mechanics of cluster growth once the initial cluster head has formed (Strom et al. 2007).

Figure 2-8 Cluster evolutionary process (Papanicolaou et al. 2003)
2.4.3. Cluster Disintegration

Brayshaw (1984) found cluster re-entrainment occurred suddenly, and the threshold for disintegration depended on the ‘calibre’ of the anchor stone, and the degree of interlock with other particles. Brayshaw (1984) also made the observation that the disintegration of the cluster resulted in the sudden release of a relatively large number of particles. This has an effect on the sediment transport rate of the stream, and determination of the threshold of incipient motion can be achieved only through the knowledge of the ‘calibre’ of the cluster.

Observations by De Jong (1991) of in-stream clusters found that cluster breakup was not necessarily dependent on the dislodgement of the anchor stone. In a primary survey, all clusters disintegrated without removal of the anchor stone. Most of these clusters showed more frequent entrainment of the stoss particles than wake particles (De Jong 1991). This would then leave the cluster available to become the anchor stone for a new cluster, shifting the emphasis for cluster stability from the calibre of the anchor stone to the cluster morphology.

A river survey was conducted where clusters were identified and then tracked after a flow event. This showed that the mode of disintegration of clusters was heavily dependent on sediment size distribution. Bimodal sediments produced larger clusters which remained stable until the anchor stone was mobilised. More uniform sediments formed clusters which were destroyed with and without anchor stone mobilisation (Hendrick et al. 2010). Clusters formed from the uniform sediment site were found to withstand the 1.5 year flood for that river.

Qualitative information describing the formation of clusters in natural conditions is readily available (Brayshaw 1984; Chin 1985; Church et al. 1998; Church and Zimmermann 2007); the amount of quantitative information in this respect is relatively sparse. In the laboratory, qualitative information on the formation of clusters is more easily available (Strom et al. 2004); however, the glass spheres that have been used are only of one size, and of a spherical shape, limiting the applicability of the knowledge to real situations.
2.5. Physical Properties of Clusters in River Bed Field Studies

The physical properties of cluster formations, and the effect of local flow and bed conditions on clusters have been investigated by a number of authors. Field surveys have shown the general behaviour of clusters in a natural environment, such as the conditions under which they form (Billi 1988; Hendrick et al. 2010; Strom and Papanicolaou 2009), their stability and effect on the sediment transport rate of the surrounding bed (Brayshaw 1984; Hendrick et al. 2010; Oldmeadow and Church 2006; Reid et al. 1992; Reid and Frostick 1984; Wittenberg and Newson 2005), or upon disintegration, how far downstream their constituent particles will be deposited (Billi 1988; De Jong 1991; Reid et al. 1992). More specific characterisation has sought to classify the different cluster shapes that occur (Hendrick et al. 2010; Strom 2006; Strom and Papanicolaou 2008; Strom et al. 2005), the geometric properties of clusters (Brayshaw 1984; Strom and Papanicolaou 2008), and the spatial arrangement of clusters (Strom and Papanicolaou 2008). These studies have provided an excellent platform from which to study clusters in more detail.

2.5.1. The Conditions Under Which Clusters Form

The location of clusters has been found to be both in the stream channel and on bars (Billi 1988; Brayshaw 1984; Buffin-Belanger and Roy 1998; De Jong 1991; De Jong 1995; Wittenberg 2002; Wittenberg and Newson 2005). All gravel rivers that have been surveyed for cluster microforms are graded gravel bed rivers, with varying grain size. Hendrick (2010) found that clusters did not form in sections of the river with water surface slopes < 1%, nor in sections with more uniform grading distributions or with smaller particle sizes (mean size of sand to 4.5 cm) (Hendrick et al. 2010). In a study with the purpose of creating a predictive formula for the presence or absence of clusters, Strom and Papanicolaou (2008b) found that clusters were most likely to form in areas of the river with riffle-pool type reaches.

The spatial distribution of clusters in rivers is determined primarily by the flow condition, which is in turn affected by the bed roughness (Wittenberg et al. 2007). Field surveys have found cluster formations are not ubiquitous, and that they occur predominantly in bars, with less frequent cluster occurrence in the main channel (Brayshaw 1984; Hassan and Reid 1990; Wittenberg et al. 2007). The occurrence of clusters in the main channel has been reported numerously in other studies, particularly in laboratory studies (Kramer and Papanicolaou
Cluster spacing has been found to be proportional to the size of the anchor stone, or $D_{90}$ of the gravel bed, and inversely proportional to the channel slope (Strom and Papanicolaou 2008; Wittenberg et al. 2007). One field study found that regardless of the sedimentological conditions of the river bed, clusters formed only around stones which were coarser than 100 mm (Wittenberg et al. 2007), suggesting that the occurrence of clusters is subject to the presence of stones greater than a threshold size.

The relative occurrence of clusters in the bed area has a proposed upper limit of around 40%, due to the turbulence around the clusters decreasing the potential for cluster formation (Wittenberg et al. 2007). Field studies of cluster formations have found the relative occurrence to be well below this value, with percentage area of cluster coverage to be within 3%-10%, 5%-10% and 7%-16% for studies conducted by Strom and Papanicolaou (2008), Brayshaw (1984) and Wittenberg and Newson (2005) respectively. Cluster formation has been observed to be regulated by a feedback process, where cluster formation either increases or decreases so the channel reaches the state of maximum resistance (Hassan and Reid 1990).

### 2.5.2. The Stability of Clusters and Their Effect on Sediment Transport

It is estimated that the incipient motion of between 50% and 70% of bed particles is delayed beyond that predicted for more exposed equivalents of like size and shape due to the presence of bedforms (Brayshaw 1985). Clusters have a notable effect on bed load transport as they are more stable than individual particles (Strom et al. 2004) and can provide bed stability either directly through the retention of sediment within the cluster formation, or indirectly by reducing the exposure of neighbouring particles (Brayshaw et al. 1983). There are two opinions about the importance of the role that the anchor stone plays in the effect the cluster has on sediment transport. Initial observations of clusters reported that the anchor stone provides stability to the constituents of the cluster, reducing the entrainment of particles within the cluster until the anchor stone is entrained (Brayshaw 1984; Hassan and Reid 1990; Reid et al. 1992; Reid and Frostick 1984). Because of the size of the anchor stone, entrainment is only likely to occur at higher flow rates. Other research based on observation of gravel rivers, suggests that entrainment of particles within the cluster occurs before the entrainment of the anchor stone, indicating that the stability of the cluster is not dependent on the size and shape of the anchor stone, and that the cluster constituents could be entrained at
relatively low flow rates, diminishing the effect the cluster has on stabilizing the bed (Billi 1988; De Jong 1991). These conflicting views may be explained by the observation that different sediment grading produces different stability in clusters (Hendrick et al. 2010), and that more bimodal beds are more likely to undergo disintegration according to the findings of Brayshaw (1984), Hassan and Reid (1990), Reid et al. (1992) and Reid and Frostick (1984). Conversely, more uniform bed material is likely to undergo disintegration according to the process described in Billi (1988) and De Jong (1991). Differences in the sediment size distribution were found to significantly affect the behaviour of clusters. The dimensionless Shield’s stress required to entrain the mean grain size of surveyed clusters was 0.06 for uniform and 0.08 for graded clusters, indicating that grading gives strength to clusters (Hendrick et al. 2010).

A survey of particles within the cluster has shown that the average distance travelled by particles is reduced when particles are involved in a cluster (Figure 2-9) (Reid et al. 1992). On average, the particles that were seeded in the stoss and wake of a cluster travelled only 54% and 35% of the travel distance of the particles that were seeded in the plane bed. Comparison of sediment transport rates between a clustered and unclustered river section demonstrated that sediment transport was lower when clusters were present and the critical Shields number was significantly higher when clusters were present (Oldmeadow and Church 2006). This study also demonstrated that clusters will reform when demolished in a reach where they had previously existed, however they take some time to gain the same level of resilience that they had prior to their removal (Oldmeadow and Church 2006). This indicates that clusters reduce the sediment transport rate of the bed in which they are present and increase the Shields number, but take some time to gain their optimum stability.
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2.5.3. Morphological Characterisation of Clusters

The shape, geometric properties and structure of clusters are all combined under the term morphology (Strom and Papanicolaou 2008). The typical formation shapes of clusters are described in Section 2.3. The geometric properties of clusters have been surveyed in various studies. Their dimensions, relative and absolute, and orientation are the major attributes that are quantified. The overall length of the cluster is influenced strongly by the size of the anchor stone. A larger stone will create more of a disturbance to the surrounding flow field, and create a larger low pressure zone downstream of the stone where the wake sediment deposits (Strom and Papanicolaou 2008). Investigations by Brayshaw (1984) found cluster length in natural rivers was between 0.1-1.2m. The relative length of the stoss and wake was variable between observed clusters, and it was proposed the length was dependent on the shape characteristics of the sediment (Brayshaw 1984). The stoss and wake each tend to

Figure 2-9 Flood average displacement of particles originating at various microform type sites at Turkey Brook River survey (Reid et al. 1992)
occupy one third of the overall cluster length (Brayshaw 1984). The length and width of clusters increased with increasing range in sediment grading and the length and width increase with a negatively skewed grading curve. The particles comprising the cluster are a variety of sizes, arranged to form relatively stable structures. Rounded particles limit the amount of interlocking, as particles are only in point contact with one another in this instance. Elongated particles have increased potential for interlocking, and tend to form imbricated trains of particles on the stoss side, and are consequently longer than clusters with rounded pebbles (Brayshaw 1984).

Sediment size distribution affects both the size and shape of bedforms (Brayshaw 1984; Strom and Papanicolaou 2008; Wittenberg et al. 2007). In well sorted sediment, bedform height decreases and spacing to height ratio increases (Wittenberg et al. 2007).

A field survey (Strom and Papanicolaou 2008) found that cluster height varied little between clusters, and was independent of the cluster shape. Clusters are generally longer than they are wide, and wider than they are high (Strom and Papanicolaou 2008). The height \((h_c)\) was more likely to be representative of the river bed composition. The same survey found that the width and length of the cluster formations were much more variable. The cluster width \((w_c)\) and length \((l_c)\) were proposed to be linearly related by the equation:

\[
\frac{l_c}{w_c} = 1.84 \frac{w_c}{h_c}
\]

where \(w_c/h_c \leq 3.5\). The linear relationship suggests that the length is a function of the height and width of the cluster causing the wake zone (Strom and Papanicolaou 2008).

Generally the orientation of the cluster has been observed to have the long axis of the cluster within 9° of the depositing flow (Brayshaw 1984). It was reported that the orientation of the constituent particles was less consistent than that of the cluster itself (Brayshaw 1984).
2.6. Physical Properties of Clusters in Laboratory Studies

The laboratory studies undertaken in the past couple of decades have illuminated aspects of the cluster formation process that would otherwise have been impossible. While some gravel bed studies have been conducted (Brayshaw 1984; Brayshaw et al. 1983; Church et al. 1998; Hassan and Church 2000), the majority of laboratory studies investigating cluster formation, particularly recently, have substituted graded gravels with uniform glass spheres (Kramer and Papanicolaou 2005; Papanicolaou and Schuyler 2003; Papanicolaou et al. 2003; Strom et al. 2004; Tsakiris 2009). This reduces the extremely complex interactions that occur when a graded bed is water worked, and enables observation of isolated variables.

The idealised experiments using glass spheres have explored some important aspects of cluster formation, and are particularly insightful as the experimental setup allows observation of the cluster formation process over the entirety of the cluster lifecycle. The type of setup used in the spherical glass beads experiments is shown in Figure 2-10. The size of the cluster is dependent on sediment availability, flow intensity and physical sediment properties such as specific gravity (Papanicolaou and Schuyler 2003). Recent experiments have explored this, focussing on the cluster formation process (Strom and Papanicolaou 2002a; Strom and Papanicolaou 2002b; Strom et al. 2004), description of cluster shape (Tsakiris and Papanicolaou 2008), the effect of sediment availability and specific gravity on clusters (Papanicolaou and Schuyler 2003; Papanicolaou et al. 2003) and the effect of relative submergence (Kramer and Papanicolaou 2005; Papanicolaou and Kramer 2006).
2.6.1. Sediment Transport in the Laboratory

A laboratory study found that the presence of clusters on the bed decreased the entrainment of particles from 87% entrainment in open-plane beds to 46% entrainment in clustered beds (Brayshaw et al. 1983). While clusters do appear to reduce sediment transport rates, the effect of armouring must also be taken into account. In artificial laboratory studies that do not use graded sediment, the armouring process can not occur, therefore resulting in exaggerated sediment transport reductions when clusters are present (Oldmeadow and Church 2006). The
rate of reduction of sediment transport caused by clusters should be determined by studies that allow armouring to also occur.

2.6.2. Cluster Formation Under Varying Flow Conditions

To investigate the formation of clusters under varying flow conditions, Papanicolaou (2002b) conducted an experiment using loose glass spheres covering 2% of the immobile glass sphere base. The incipient flow condition, $\tau_{cr}$, was determined as the flow rate at which marginal movement occurred on the bed. Cluster formation was found to occur and dominate the bed topography in the range of $1.25\tau_{cr}$ to $2.0\tau_{cr}$ (Strom and Papanicolaou 2002a; Strom et al. 2004). The level of stress present at which clusters form was found to affect their arrangement. Increased stress caused the spacing of clusters in the direction of the flow to increase, however spacing perpendicular to the direction of the flow was unaffected (Strom and Papanicolaou 2002a; Strom et al. 2004).

When the surrounding shear stress becomes too great the cluster disintegrates. Strom, Papanicolaou et al. (2004) found that at $2.25\tau_{cr}$, partial and complete disintegration of clusters began to occur, and at $3.0\tau_{cr}$ or greater, general bed motion occurs, and all cluster microtopography is eventually eliminated (Strom et al. 2004). Other studies found similar results, where some of the clusters that formed stayed stable up to $3.0\tau_{cr}$ or greater, demonstrating the added stability clusters can add to the river bed (Strom and Papanicolaou 2002a).

Observations of spherical glass beads at differing shear stresses have indicated that cluster spacing is dependent on the bed shear stress. The streamwise distance ($\lambda_x$) between clusters increases with $\tau_o$, but the transverse spacing ($\lambda_y$) is independent of this, as can be seen in Figure 2-11.
2.6.3. The Effect of Specific Gravity on Cluster Formation

Observation of the effect of specific gravity has been detailed in a number of reports (Papanicolaou and Schuyler 2003; Papanicolaou et al. 2003; Schuyler and Papanicolaou 2000) using a combination of spherical glass and Teflon beads with differing specific gravity (2.58 and 2.12 respectively). Specific gravity was found to affect cluster size and shape in some cases. In experiments with equal proportions of Teflon and glass beads, the clusters that formed were smaller, and the bed was more dynamic than in experiments with glass beads only (Papanicolaou et al. 2003). An earlier study found that with equal proportions of glass and Teflon beads, the size of the clusters increased. It was also observed that the lesser the specific gravity of the particles, the smaller the size of the cluster. Increased specific gravity also creates a more variable and slower approach to equilibrium for the bed surface in the clustering experiments (Schuyler and Papanicolaou 2000)

![Figure 2-11 Cluster spacing normalised by particle size, as a function of the bed shear stress (Strom and Papanicolaou 2002b)](image-url)
2.6.4. The Effect of Sediment Availability on Cluster Formation

To investigate the effect of sediment availability on cluster formation a study was conducted using spherical glass beads. Cluster formation was monitored when moveable spheres covered 2%, 35% and 50% of the test area surface (Papanicolaou and Schuyler 2003; Papanicolaou et al. 2003).

For the case with only 2% surface coverage, at incipient flow conditions, cluster shape was generally in heaps. As the flow increased to two times the incipient flow condition, clusters formed rhomboidal and triangular shapes. The clusters at this availability consisted of two particles on average. It was observed that the 2% condition produced clusters which most closely resembled those formed in natural streams (Papanicolaou and Schuyler 2003; Papanicolaou et al. 2003). The 35% availability case produced clusters generally in ring shapes and in elongated heaps at the incipient flow condition. When the flow rate was increased to twice the incipient flow rate, the clusters disintegrated. The average cluster at this availability consisted of 32 particles (Papanicolaou and Schuyler 2003; Papanicolaou et al. 2003). The 50% availability case formed paved layers of spheres which did not conform to any specific cluster shape. On average, at the 50% availability, clusters contained an average of 75 particles per cluster (Papanicolaou and Schuyler 2003; Papanicolaou et al. 2003).

2.6.5. The Effect of Relative Submergence on Cluster Formation

Relative submergence is the ratio between the specific grain size and the water depth. The anchor stone is generally used for the grain size, where its size is represented by the $D_{90}$. The effect of relative submergence was investigated by Kramer and Papanicolaou (2005), and Papanicolaou and Kramer (2006) where both studies divided the submergence ratio into low and high relative submergence. Low relative submergence was defined as being a ratio of less than 3, while high relative submergence applied to a ratio greater than 3.

The relative submergence is important as it changes the interaction between the flow and the sediment. When the flow depth is in the same order of magnitude as the anchor stone, the interaction between the flow and particle dominate the flow mechanics of the water column. This, in turn, affects the deposition of sediment surrounding the particle (Papanicolaou and Kramer 2006). At low relative submergence, the critical shear stress of the flow is dependent on the Froude number, whereas at high relative submergence, the flow is governed by the Reynolds particle number ($R_p$) (Papanicolaou and Kramer 2006)
Observations from both studies found that at a low relative submergence, the clusters that formed were more elongated, forming streak shapes. High relative submergence produced clusters with random formation in a variety of shapes. In the experiments for this study, both the cases of high and low relative submergence acted as a sink for sediment deposition. However the low relative submergence case had a lower rate of exiting sediment than the high relative submergence case, indicating more effective retention of suspended sediment (Kramer and Papanicolaou 2005; Papanicolaou and Kramer 2006). Observation of the results from Papanicolaou and Kramer (2006) show that at low relative submergence the deposition of particles was primarily in the stoss region, whereas at high relative submergence particles generally came to rest in the wake region (Papanicolaou and Kramer 2006).

2.6.6. The Effect of Cluster Microforms on Bed Roughness

Cluster formations have been identified as a major influence on the roughness of riverbeds. The identification of clusters and their size and shape therefore affects the roughness coefficient which is widely used in engineering.

Roughness length has typically been quantified using the grain size distribution. Tsakiris (2009) suggested a reliable roughness parameter for beds containing cluster formations should take into account not only the grain size distribution of the river, but also the size and shape of the cluster formations in the bed (Tsakiris 2009). Combining information on the grain size distribution of the bed with the spatial distribution of clusters can provide sufficient information as the cluster height is predictable by the grain size (Strom and Papanicolaou 2008). Clifford et al. (1992) proposed a proportionality constant to use in conjunction with the grain size distribution, to account for the grouping of sediments into bed forms. He proposed that roughness \( k \) is proportional to the grain size of the bed, \( k = (3.0-3.5)D_{84} \) or \( k = 6.8D_{50} \) (Clifford et al. 1992).

Bed surface roughness may also be described by evaluating the distribution of bed surface elevations \( z(x,y,t) \) spatially in an \( x,y \) plane over time \( (t) \). Aberle and Nikora (2006) investigated the statistical properties of armored gravel bed surfaces, which showed that the Probability Distribution Function (PDF) of bed elevations increases in range and the number of elevations around zero mean decreases. The standard deviation of the range in bed
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elevations was used as a quantification of the characteristic vertical roughness length of gravel beds (Aberle and Nikora 2006).
2.7. Prediction of Clusters in Rivers

Research into clusters has included efforts to evaluate the effects of particular attributes of the river system on cluster mechanics. The effect of different variables on the likelihood and properties of cluster formation has been evaluated in controlled laboratory experiments (Strom and Papanicolaou 2008). The variables affecting cluster formation can be divided into two categories; particle scale, and reach scale. The particle scale refers to the immediate environment and local characteristics of one particular cluster, where the reach scale refers to the attributes of the few metres in the channel surrounding the cluster.

2.7.1. Local Scale Predictive Formulae

The occurrence of clusters is fundamentally dependent on the selective transport of grains, which is related to turbulence in the local flow field. The factors affecting the formation of clusters at the particle scale were presented by Strom and Papanicolaou (2006) as follows:

\[ C = f_2(\tau_{\alpha}, \tau_{cr}, D, \sigma_g, s) \]

Where \( \sigma_g \) is the geometric standard deviation of the particle size \( C \) is a binary variable representing the likelihood of clusters occurring on the river surface, for which \( C = 1 \) represents a dominant presence of clusters, and \( C = 0 \) represents sporadic cluster occurrence. There is currently no formula developed to describe cluster formation as a function of the relevant local variables, however research has been conducted into the qualitative effect of individual parameters on cluster formation (Papanicolaou and Schuyler 2003; Papanicolaou et al. 2003; Strom et al. 2004).

Investigation into local scale effects on cluster formation is best suited to laboratory investigation. To date the effects of specific gravity, relative submersion, sediment availability and flow rates have been observed in controlled environments, as discussed in Section 2.6.

2.7.2. Reach Scale Predictive Formulae

While cluster formation is generally determined at the particle scale for the local flow and bed structure, the wider reach also can influence formation (Papanicolaou et al. 2003). It has been proposed that the local particle conditions are interdependent with the reach-scale flow and geomorphic conditions, resulting in the extended effect of larger scale events influencing
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cluster mechanics (Papanicolaou et al. 2003). Considering this, Strom and Papanicolaou (2008) proposed a relationship incorporating variables from the wider reach that are indicative of the potential for cluster formation. Using the same indicator ‘C’ to measure the likelihood of clusters occurring in the reach, they suggested the presence of clusters in the wider reach of the river was subject to the following variables:

\[ C = f(g, \rho, \rho_s, Q, S_{eq}, h, w, D_{50}, D_{84}) \]

where \( \rho_s \) is the density of the sediment, \( Q \) is the bankfull discharge, \( S_{eq} \) is the reach slope, \( h \) and \( w \) are the bankfull height and width, and \( D_{50} \) and \( D_{84} \) are the grain sizes for which 50% and 84% of the reach sediment is smaller, respectively. These variables were arranged into non-dimensional parameters to alleviate site specificity. The importance of the stream morphology in influencing cluster formation is highlighted in the functional parameters proposed by Strom and Papanicolaou (2006) for predicting cluster occurrence. In addition to the variables proposed by Strom and Papanicolaou (2008), they included the term \( M \), which is a parameter to describe the morphology type of the reach, e.g. whether it is a step pool, plane bed or riffle pool.

A number of natural streams were surveyed to obtain data for testing the importance of the variables in predicting cluster occurrence (Papanicolaou et al. 2003). River reach scale variables and the presence or absence of clusters in each reach were recorded. By determining the sedimentary and hydraulic conditions indicative of cluster formation, prediction of cluster occurrence becomes possible. A connection between the dimensionless parameters \( w^* = w/D_{84} \) and \( Q^* = wQ^2/gD_{84}^6 \) and the occurrence of clusters on the river bed was observed (Papanicolaou et al. 2003). These parameters are good indicators of cluster occurrence due to their encompassing descriptiveness of the channel reach sedimentary and hydraulic conditions.

Relationships describing the probability of cluster occurrence using the non-dimensional reach scale parameters proposed by Strom and Papanicolaou (2008) were developed using statistical analysis, and are as follows (Papanicolaou et al. 2003):

\[ \pi(w^*) = \frac{e^{-6.85+1.39\ln(w^*)}}{1+e^{-6.85+1.39\ln(w^*)}} \]  \hspace{1cm} (20)

\[ \pi(w^*Q^*) = \frac{e^{-4.29+0.23\ln(w^*Q^*)}}{1+e^{-4.29+0.23\ln(w^*Q^*)}} \]  \hspace{1cm} (21)
where $\pi(x)$ is the probability that $C = 1$. These equations were found to have a fair accuracy in predicting clusters (Papanicolaou et al. 2003).

In research of a similar nature, surveys conducted by Wittenberg, Laronne et al. (2007) on natural stream beds determined three significant variables involved in cluster concentration. These were the $D_{90}$, sediment sorting and channel slope (Wittenberg et al. 2007). The authors of the study claim that these three variables are auto-correlated, as sorting is related to sediment coarseness, and grain size distribution is broadly related to channel slope. Sediment sorting is identified as being most statistically significant for determining cluster formation, where the greater the range in sediment sizes, the larger the proportion of clusters that cover the bed (Wittenberg et al. 2007). No formula was developed to describe this effect, however the correlation coefficient between grading and cluster coverage was $r^2 = 0.80$ (Wittenberg et al. 2007).
2.8. Flow Around a Cluster

2.8.1. Flow Structure Measurements Around Instream Pebble Clusters

The presence of protruding particles as constitute clusters, creates rapid transitions in the river bed roughness. These roughness changes directly affect the turbulent length scales and spatial patterns of the mean and turbulent flow properties (Lacey et al. 2007). The primary cause for these changes is the vortices created in the lee of the protruding stone. Lacey et al. (2007b) compared the turbulent flow field surrounding a cluster to that in the same riverbed with the cluster removed. The results of their test showed a twofold increase in turbulent kinetic energy surrounding the cluster when the cluster was present (Lacey and Roy 2007b). A later study by the same authors was conducted, in which they observed the finescale turbulence characteristics downstream of a cluster (Lacey and Roy 2008). These observations indicated that two vortex shedding modes were present in the wake; a small scale high frequency initial instability mode and a lower frequency mode that scales with cluster height. Longitudinal vortex shedding was identified as dominant in the wake. These were characterised by turbulence ejections and sweeps, where the shear layer was seen to expand and contract respectively with the passing of these events (Lacey and Roy 2008).

Buffin-Belanger (1998) conducted a field study on the velocity fields in turbulent flow upstream and downstream of a pebble cluster. The velocity vectors along the centreline of the cluster were measured. Their measurements provide an excellent description of the complex interactions that occur in the flow field around the cluster. It was observed that velocity vectors upstream of the cluster increased with vertical distance from the bed, and displayed slightly downward motion. Flow over the top of the cluster accelerated as the relative water depth reduced, and motion was upward. Immediately downstream of the anchor stone the flow velocity was significantly reduced and motion was recirculating (Figure 2-12). Directly downstream of the cluster, the velocity of the flow decreases and a zone of eddy shedding is characterised by intense turbulence. The flow direction changed from being predominantly downward with some upward events, to predominantly upward, with some downward events (Figure 2-13). Further downstream velocities remained low and motion was primarily upwards, eventually returning to the same conditions as upstream (Buffin-Belanger and Roy 1998). Investigation into the field of turbulent flow around the cluster revealed six regions: acceleration, recirculation, shedding, reattachment, upwelling and recovering flow. These regions have shifting boundaries with high shear zones separating them (Buffin-Belanger and
Roy 1998). Clusters also have a major effect on the three dimensional flow structure. Figure 2-14 shows the horizontal plane of the flow field at half the height of the cluster. The obstruction created by the cluster diverts the approaching flow vectors to either side of the stones, while further downstream they converge (Figure 2-14).

Inspection of velocity profiles over the centreline of a cluster with high relative submergence ($h/h_c = 11.8$) found that the flows were only affected in the wall region of the flow ($y/h \leq 0.2h$) with the exception of the profile over the centre of the cluster, which shows an acceleration of flow until $y/h = 0.46$ (Strom et al. 2007). Within the wall region, the effect of the cluster on the velocity profile varied with position along the cluster. The flow in the stoss region was retarded, showing a slower velocity profile than the uninhibited flow (Strom et al. 2007). The logarithmic distribution of flow held in the velocity profiles taken up and downstream of the cluster where there was no disturbance of the flow. The logarithmic distribution broke down in the near wall sections over the cluster and was not valid until $y/h > 4.6$ over the centre of the cluster (Strom et al. 2007).
2.8.2. Numerical Modeling

Strom et al. (2007) researched the flow structure around a naturally formed cluster of spherical particles using both measurements of the velocity profile at points along the centreline of the cluster, and using Reynolds Averaged Navier-Stokes (RANS) turbulence modelling with the Menter Shear Stress Transport model to numerically simulate the flow. A mesh grid was created to imitate the formation of the cluster, where the particles were represented as flat-topped, sloping-sided polygons with the same footprint and height as the experimentally formed clusters.

Figure 2-15 shows an image from this simulation. The flow path around the cluster formation at a height less than the height of the cluster is strongly affected by the presence of the cluster. The flow at this height is deflected to the side and over the top of the obstruction. The flow which was deflected upwards subsequently plunges downwards downstream of the obstacle. A series of small recirculation zones within the larger trend of flow in the wake of the cluster were observed. A horseshoe vortex phenomenon was not observed in this simulation, which could have been due to limitations in the use of a steady state RANS model which is likely to average out any unsteady coherent motion (Strom et al. 2007).
2.9. Photogrammetry

Photogrammetry is the method of using photographic images to obtain quantitative data about a surface. The advancement of digital cameras has allowed for improved image capture and less labour intensive analysis. Sediment movement has typically been measured using sediment traps to record the bedload movement over time. This has the disadvantage that the traps can be intrusive and affect the flow and results (Radice et al. 2006). Research into particle tracking of sediment has commonly utilized the technique of ‘tagging’ particles to aid observation. Historically sediment transport studies have used radioactive and fluorescent substances to coat natural sediment in field studies (Black et al. 2007). Synthetic sediments have also been used, such as coloured plastic beads (Schuyler and Papanicolaou 2000), which are desirable as they avoid the difficulty of painting the particles, however they have different specific gravity and shape to real sediment. As photogrammetry is completely external it has minimal or no affect on the flow and it also has the advantage of taking instantaneous images, allowing investigation into the behaviour of particles during an experiment.

The development of image analysis algorithms allows for quick processing of long sequences of photographs. These provide output showing the behavioural trends of sediment over extended periods of time. Algorithms can be developed to investigate a number of features of sediment transport. These can be categorised into two areas of study; firstly, overall trends of sediment movement and secondly, studies of individual particles. Overall trends can be used to determine how surface formations or the grain size distribution of a river bed change with time (McEwan et al. 2000), highlighting phenomena such as armouring. Specific studies can give insights into the behaviour of sediment microforms, and are useful for the study of sediment entrainment. Specific information, such as particle velocity, can be analysed to give statistics on the properties of a bed (Li et al. 1997).
2.9.1. Using a Fixed Bed and Coloured Particles

In an effort to overcome the difficulty in distinguishing moving particles from a similar bed in plan-view photogrammetry, some authors have used moveable coloured particles on a different coloured fixed bed (Schuyler and Papanicolaou 2000; Strom and Papanicolaou 2002b). This technique allows the visual identification of the moving particles through a thresholding technique, where all colours darker (or lighter) than a particular light intensity can be extracted. This technique is excellent for the study of individual particles, however study of the dynamics of the entire bed is not permitted, as it relies on a fixed bed of different coloured particles.

Radice et al (2006) conducted image analysis on a series of experiments in order to improve the method of quantifying sediment transport. In this instance only sediment transport in the upper layer was active, ensuring that observation from above was sufficient. Sediment transport in this case occurs with some sediments remaining still for periods of time, while others are entrained (Radice et al. 2006). A later study using Fluid Stream software (Nokes 2007) to assist particle tracking has shown considerable advancement and potential in tracking natural sediments, however the desired reliability of measurement for the study was not achieved (Radice et al. 2010).

2.9.2. Cluster Photogrammetry to Date

Schuyler and Papanicolaou (2000) developed a method of using digital imaging combined with computer programming to analyse cluster formations relatively easily. This was a large advance from traditional techniques such as using still photography combined with manual identification of clusters. To monitor the cluster development, Schuyler and Papanicolaou (2000) placed a video camera above the test section of the flume to record a 30-40 cm wide plan view of the experiment. The video recording was digitised by the Assymetrix Video Capture 4.0 programme, where individual images were digitised at sequential instants. High frequencies of images were isolated at the beginning of the experiment due to initial high bedload movement, and lower frequency digitisation was used as the experiment progressed. Adobe Photoshop 4.0 was used to convert the images to TIFF (Tagged Image File Format) format, then the images were imported into the image processing and analysis programme Global Lab Image Software version 3.0 (Schuyler and Papanicolaou 2000).
The image processing methodology was divided into four steps. The first step was to identify the region of interest (ROI), which is the region within the image which contains the beads used for the clustering experiment. The second step was to define the upper and lower greyscale threshold values by determining the pixel intensity of the lightest and darkest areas of the particles. The third step was to identify the area boundary conditions by determining the average pixel area of a particle. The fourth step was to identify the number of clusters in a ROI where a cluster was any grouping of two or more particles (Schuyler and Papanicolaou 2000).

Strom and Papanicolaou (2002b) followed a similar process in their cluster analysis technique. Using a digital video camera and Adobe Photoshop they firstly determined the number of pixels in one sphere and used it as a reference length to measure cluster properties. An example of their application is shown in Figure 2-16, which shows the movements of particles joining and leaving an individual cluster. This technique allows continuous collection of information pertaining to clusters at a level of detail that would otherwise be extremely time consuming.

![Figure 2-16 Time series of deposition (joining) and erosion (leaving) of particles in and out of a cluster (Strom and Papanicolaou 2002b)](image-url)
Chapter 2. Literature Review

2.10. Literature Review Summary

Over the past few decades, investigation into cluster formations has been established and has gained attention. A number of insightful studies have been conducted focusing on both natural river systems and laboratory studies.

Clusters have been found to play an important role as habitat for micro-invertebrates in river environments. They are thought to add structure to the bed surface, enhancing the stability of the bed and playing a role in reducing the amount of erosion that occurs in floods. Investigation has provided insight into the physical attributes of clusters, where different cluster shapes have been identified and quantified by their relative occurrence. The conditions under which clusters form have been surveyed, and predictive formulae have been developed to evaluate the likelihood of cluster occurrence on a river bed.

The behaviour of clusters as they form and disintegrate has been studied under idealised conditions as has the effect of variable flow and sediment conditions. A number of studies have investigated the dynamics of the flow surrounding clusters, where both physical studies as well as computational modelling have been employed.

This archive of research provides a solid background from which to continue investigation. While extensive, the topic is still not completely understood, leaving room for new research and advances in understanding to be achieved.
Chapter 3. Experimental Methodology

3.1. Introduction

The aim of the present study was to investigate the development of naturally formed cluster microforms from a flattened bed of graded gravel at constant flow rate. These experiments act as a bridge between the group of laboratory experiments conducted on idealised glass spheres and field studies conducted on naturally formed clusters. The study was laboratory based, and used photogrammetry to observe the behaviour of well graded, cohesionless sediment at flood flow conditions as clusters formed, evolved and disintegrated. Focus was primarily on the cluster formation and sediment movement. Physical limitation of the study meant that only limited flow information was available.

A series of experiments were conducted, testing the response of cluster formation to different flow and sediment conditions. Three main variables were investigated for their role in cluster formation. The variables tested were:

1. Change in flow rate
2. The addition of a significantly larger anchor stone on the bed
3. Change in sediment grading

All of the experiments were conducted in the same flume, with the other variables kept constant between experiments.

The experiments were conducted over a number of hours, to allow for clusters to develop fully. The test section of the experiment was photographed continually to capture the behaviour of the sediment. Post processing of these images, using novel image analysis techniques (described in Chapter 4), provided the majority of the data in this study. Supplementary information regarding the velocity profile, and topography of the initial and final bed arrangement was also collected from the experiments.

The experimental work and analysis was conducted in the Fluid Mechanics Laboratory of the Civil and Environmental Engineering Department at the University of Auckland.
3.2. Experimental Equipment

3.2.1. Flume

Experiments were conducted using a 19m long flume with dimensions 0.45 m wide by 0.5 m deep. A photograph of the flume is shown in Figure 3-1 and a cross-section along the length of the flume is shown in Figure 3-2. The slope of the flume is adjustable, as it is supported by a truss structure with a central pivot and manually operated screw jacks. The flume has a maximum achievable slope of 0.015. The flume is equipped with a false floor leading up to a recess in which the sediment can be placed. There are also rails along the length of the flume to enable a travelling carriage. The carriage is fitted with measuring equipment where vernier scales allow adjustment of position of equipment in three dimensions to a high accuracy.
Figure 3-2 Cross-section along length of flume
Water is supplied to the flume using pumps that draw from a constant head reservoir. Two pipes of 150 mm and 250 mm diameter deliver water to the flume. The maximum pump capacity is approximately 255 l/s and the maximum discharge from the pipes is approximately 200 l/s. Temperature is kept constant at 21°C using a cooling system within the reservoir. The water level is controlled by an adjustable sharp crested weir at the end of the flume. After passing through the flume, all water is returned to the reservoir.

Discharge to the flume is measured using an orifice plate in the supply line and discharge is regulated by butterfly valves. Upon entering the flume, the water first passes through a mesh screen to smooth the flow, then passes through a flow straightener. The flow straightener is a matrix of thin sheet metal 0.45 m wide 0.45 m deep and 0.65 m long where the width and depth are divided into 50 mm square cells. The 130 mm high false floor is installed in the flume from 2 m downstream of the straightener to 5 m before the weir at the flume end.

3.2.2. Sediment Recess

The sediment recess is situated 10.43 m downstream of the flow straightener. The recess is 1 m long, 0.45 m wide and its depth is the full thickness of the false floor. Fitted within the recess is a 5 mm thick plastic table with foam at the interface between the table and the side walls to prevent sediment falling through the cracks. The plastic table is supported by four mechanical screw jacks which are connected to a motor below the flume. The motor drives a chain around cogs attached to the screw jack, enabling the jacks to adjust the height of the plastic table within the recess. The speed of the motor is adjustable, with a minimum speed equating to a vertical rise of 0.17 mm/min and maximum speed delivering a vertical rise of 1.4 mm/min.

The sediment recess provided two major advantages to the execution of the experiment:

1. The adjustable bed allowed the test section surface to remain level with the upstream fixed bed as the section eroded. This ensured the bed shear stress was kept relatively constant and reduced the complicated flow structures that would have exaggerated scour if the levels were to become uneven.

2. The volume required to fill the sediment recess was relatively small. The volumes required to work with a larger section of the bed would have been unmanageable considering the steps that must be taken for the execution of these experiments.
The adjustment of the sediment recess while experiments were underway was undertaken manually. The position of the upstream edge of the sediment recess in relation to the fixed bed was monitored regularly during each experiment. If the test bed level appeared reduced, the adjustable bed was raised until the two surfaces were level once again.

A disadvantage of the adjustable sediment table technique is the level of manual input required. The three dimensional variability of the water worked surface makes judgement of when the surface is ‘too low’ difficult. For these experiments, if two or more stones of size coarser than the $D_{80}$ were below the level of the fixed bed, the adjustable bed was raised.

### 3.2.3. Fixed Bed

The roughness of the bed upstream of the sediment recess was fixed to prevent a change in flow conditions upon entering the test section. Armoured surfaces are known to consist of mainly the coarsest 20 to 30% of the bed material (Chin 1985). Therefore, pebbles from the largest 30% of the grading curve were glued to the upstream fixed bed. This armoured surface extended for 2 m upstream of the test section. The same process was conducted for the entire fixed bed downstream of the test section.
3.3. Materials Used

3.3.1. Sediment Properties

Rounded river gravels ranging from 0.15 to 50 mm were used in the experiments. There was no upstream sediment source. The sediment grading of the sediment in the test section was modelled on the experiments conducted by Chin (1985). The gravels were sourced from the local landscaping company Stone and Water World, Auckland. A major feature of the experimental set up was the use of colour to identify the size of the sediment. The sediment was separated into five size groups approximating the important fractions involved in cluster formation. The average properties of these sizes are shown in Table 3-1.

The shape factor is defined as \( SF = \frac{c}{\sqrt{ab}} \), where \( a \) (longest), \( b \) (medium) and \( c \) (shortest) are mutually orthogonal dimensions of a particular grain. A vernier calliper was used to measure the grain dimensions of a sample of 100 grains. Grains smaller than 2.8 mm were not measured, however observation showed they were similar in shape to the coarser grains.

<table>
<thead>
<tr>
<th>Sediment Colour</th>
<th>Size range (mm)</th>
<th>( D_{av} ) (mm)</th>
<th>Specific Gravity (SG)</th>
<th>( SF = \frac{c}{\sqrt{ab}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grey</td>
<td>0.15 - 2.8</td>
<td>1.5</td>
<td>2.71</td>
<td>-</td>
</tr>
<tr>
<td>Yellow</td>
<td>2.8 - 4.5</td>
<td>3.65</td>
<td>2.73</td>
<td>0.5</td>
</tr>
<tr>
<td>Green</td>
<td>4.5 - 9.5</td>
<td>7</td>
<td>2.73</td>
<td>0.51</td>
</tr>
<tr>
<td>White</td>
<td>9.5 - 25</td>
<td>17.25</td>
<td>2.72</td>
<td>0.55</td>
</tr>
<tr>
<td>Red</td>
<td>25 - 27</td>
<td>26</td>
<td>2.73</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Table 3-1 Bed material properties

3.3.2. Sediment Production

The division of the grading curve into the painted fractions is shown in Figure 3-3. The colours red, white, yellow and green were used, leaving the smallest size group (<2.8 mm) unpainted. The gravels were painted using spray enamel purchased from Colour Works Paint Supplies in Auckland. The gravels were laid out flat and coated with paint using a spray gun, then left to dry, roughly turned, and sprayed again. For the fractions with a wide range in gravel size, the gravel was separated into two size groups and painted separately, as the smaller gravel particles tended to fall to the bottom and receive less paint coverage than the larger sized gravel. This process was repeated until sufficient coverage was achieved. Care
was taken not to coat the gravel too many times as this would enlarge the gravel size, consequently altering the grading curve.

![Division of grading curve into different colours](image)

The painted gravels were mixed manually and then transferred into the test section; some problem was encountered with the smallest fraction of the gravel falling quickly to the bottom. The same batch of gravel was used for all experiments. After each experiment, all the gravel that had been transported downstream was vacuumed up; the sediment was remixed and then placed back in the test section. Sieve samples were taken regularly, after experimentation, to ensure the grading curve remained the same.

### 3.3.3. Water Height

Determination of the water height requires consideration of the effect of the flume walls and sediment roughness on the flow formation. Shear stresses in the water are important for representing the flow properties, and factors which influence the shear stress must be monitored. There are two constraints which affect the development of shear stress in the flume. Firstly, when the ratio between the flow depth and the equivalent roughness, $y_0/k_s > 6–7$, the logarithmic velocity law stays true. Secondly, when the ratio of channel width to flow depth, $b/y > 8$ the effects of the side walls on the flow are greatly reduced (Chin 1985). Ideally both of these constraints should be satisfied when determining the flow depth. In
cases where this was not possible, Chin (1985) gave priority to maintaining the logarithmic velocity law as this was used to determine shear velocities, this study has done the same.

3.3.4. Bed Placement

The method of placement of gravel in laboratory experiments has an effect on the structure of the sediment in the test area. An investigation was conducted to compare a manually prepared screeded bed with a sediment fed bed (Cooper and Tait 2008). The study found that the sediment fed bed created a bed with structure and complexity, similar to that of a naturally formed bed. In comparison, the screeded bed had random grain organisation, and measurements of the near bed velocity of the flow revealed a reduction in the degree of temporal variability of the flow (Cooper and Tait 2008).
3.4. Instrumentation

The instrumentation used in these experiments was photogrammetry equipment, Acoustic Doppler Velocimetry (ADV) and an acoustic depth sounder. Photogrammetry was the main source of data, and the flow and surface information was supplementary. Figure 3-4 shows a streamwise cross section of the test section, with all relevant instrumentation, which will be discussed in the following sections.

3.4.1. Photogrammetry

Photogrammetry is the process of obtaining geometric properties from a photographic subject. In these experiments, one overhead camera was used to continuously photograph the test section below, providing a two dimensional perspective of the particle movements in the stream-wise and transverse directions. The acquisition of 3D data, called stereo-photogrammetry, requires the use of a second camera and was not conducted in these experiments.

3.4.1.1. Cameras

Two cameras were used in this research:

- Nikon D90 - primary
- Casio EXILIM Pro EX-F - supplementary
For high quality full colour images, the Nikon D90 digital SLR camera was chosen as a cost-effective solution. The lens used was an AF-S Nikkor 18-105 mm, which was supplied with the camera. This camera was used as the primary tool, providing high resolution continuous imaging of all of the experiments conducted. The Nikon could be connected to a computer to allow remote control and immediate download of the image to the computer’s hard drive. This camera was used to take still photos at a rate of approximately 1.5 per second for the duration of the experiment which was a high enough frequency to capture the movement of larger particles in the test section. The battery life of the camera when used in this capacity was approximately 4 hours. This allowed constant image acquisition for this duration, after which the battery needed replacing.

A Casio EXILIM Pro EX-F digital camera was chosen as an affordable, practical video camera to be used when higher frame rates were necessary. The video captured images at a rate of 30 fps, which was a fast enough frequency to capture most movement on the bed. The image size however, was not large enough to capture high resolution images of the entire bed, so only sections of the bed were captured on video. The limitation with using this camera was that the flash memory for these cameras is of FAT32 format, which has a file size restriction of 4GB. Employing the camera in HD mode thus results in a maximum clip size of 4 GB per file, which translates to around 16 minutes. In addition, Casio does not support direct computer control for the Pro EX-F, thus media collection was interrupted to allow for the 4GB file size restriction. In our case, the memory in use was a 16GB SDHC card, allowing interrupted capturing of 64 minutes of footage, which needed to be downloaded to the computer frequently when intended for longer use. This disrupted image collection and risked changing the position of the camera, thereby taking subsequent images of a slightly different section of bed and making analysis more difficult.

3.4.1.2. Camera Setup

The arrangement of the camera and setup is shown in Figure 3-5. The test section was equipped with an overhead frame on which the camera was held steady. The camera was attached to the laboratory computer. In some experiments a tripod was set up next to the flume for a second camera to capture a side view of the test section, or a second camera was also positioned above the test section. Four dual flood lights were positioned around the test section.
3.4.1.3. Flow Skimmer

To eliminate distortion of the image from reflection and refracting light caused by fluctuations of the water surface, a 1 m long Perspex skimmer was fabricated. This ‘flow skimmer’ was adjustable and could be made to sit lightly on the surface of the water so that any surface waves were flattened but minimal disturbance was caused to the channel of water and pressurisation was minimal. One problem with the skimmer was the presence of bubbles which were created due to the obstruction created by the upstream end of the skimmer. These would flow under the skimmer, thus being present on the recorded images and negatively influencing the forthcoming image analysis. Consequently, these bubbles were minimised by adding an additional skimmer upstream to flatten the water entering the test section, and adding a streamlined ‘V’ shape to the upstream side of the skimmer to divert any bubbles to the edges of the skimmer, where they would not influence the image analysis.

The flow skimmer was positioned as lightly on the flow surface as possible to reduce any effect on the flow properties. The presence of the flow skimmer on the surface prevented the use of the ADV in the test area so the effect of the skimmer was not able to be quantified. To gain an estimate of the effect, two centreline velocity profiles were taken; one directly downstream of the flow skimmer on the test section, and another in the same position but with the flow skimmer removed. The results of these two experiments are shown in Figure

Figure 3-5. Photograph of flume setup
3-6. The shear velocity \((u^*)\) for the two cases was calculated to be 0.074 m/s with the skimmer and 0.071 m/s without.

![Figure 3-6 Velocity profile of test bed with and without flow skimmer](image)

### 3.4.2. Acoustic Doppler Velocimeter (ADV)

The ADV is a single point high resolution current meter that measures the flow in three dimensions. The ADV comprises of a central probe with three receivers extending outward (Figure 3-7). The probe transmits an acoustic wave at known frequency, which bounces off particles in the flow and is received by the three receivers which record the frequency of the rebounded wave. The Doppler Effect is utilised in determining the velocity of the particles, the velocity of the particle being proportional to the shift in frequency of the emitted wave. The receivers measure the velocity of particles within the test volume, which is situated 50 mm lower than the probe. The remote sensing capability of the ADV is advantageous as it can measure the flow velocities without disturbing the sample. The free accompanying software WinADV was used to process the data. Filtering was done using a minimum of 70\% correlation, and minimum 15\% SNR.

Velocity profiles were recorded upstream of the test section with the ADV for all tests. To test the uniformity of the flow, velocity profiles were collected at multiple positions upstream and within the test section for one experiment. This facilitated the comparison of flow distributions approaching the test section with the flow distribution throughout the test section. The existence of uniform flow was verified (Appendix II).
3.4.3. Acoustic Depth Sounder

The acoustic depth sounder (DS) was used to record the surface level of the gravel bed at the start and finish of each experiment. The sounder emits high frequency ultra-sonic waves (2-MHz) that are reflected off the surface and received back by the probe. The time taken for the waves to return is measured by the probe, and the constant speed of the waves means the distance is proportional to the measured time. The sounder provides longitudinal readings at 2.54 mm intervals with a vertical accuracy of ±0.4 mm (Coleman 1997). The sounder is positioned vertically on the carriage; the longitudinal distance travelled along the flume is measured by a potentiometer that is connected to a 20 mm wheel that rotates as the carriage is pushed along the flume. Vertical profiles were taken every 2.45 mm in the transverse direction, ultimately providing a mesh of data points with 2.45 x 2.54 mm spacing.

The longitudinal reading was subject to some error; when the wheel was wound back to the starting point often some distance would be lost, requiring the need for a start indicator. This took the form of a removable metal lip at the start of the test section (Figure 3-8).

The level detected by the sensor was subject to some noise, with on average each length of the test section having two points that were falsely read (Figure 3-8). This was smoothed using Matlab, with an algorithm that replaced any point that was 5 mm greater or lower than...
the adjacent data point in the transverse direction. This outlier was then replaced with an average of surrounding data points that were within the 5 mm threshold.

Figure 3-8 Data from DS prior to filtering
3.5. Formation of Clusters Experiments

The formation of clusters was observed under various conditions. These different environments were used to help create a clearer picture of what influences cluster formation and disintegration. The variable experimental conditions were:

- flow rate (60, 66, 72 l/s)
- the addition of a large anchor stone
- the addition of many anchor stones
- different grading curves

3.5.1. Summary of Experiments

A summary of the experiments that were explored using photogrammetry is presented in Table 3-2. The experimental nomenclature uses the following method; the presence of an artificially placed anchor stone is denoted by an ‘A’, where A0 indicates no anchor stone was placed, A1 indicates the large round type anchor, and A4 indicates the large oval flat anchor. G describes the grading curve of the sediment, described further in Section 3.5.4 and the final two numbers refer to the flow rate at which the experiment was run.

The flow rate \( Q \) is that measured by the orifice plate of the flow entering the flume, the shear velocity \( u^* \) is that measured using the velocity profile recorded by the ADV, the \( D_{50} \) and \( D_{98} \) relate to the subsurface material, sieved prior to placement in the test section, \( t_{max} \) is the experiment duration and the \( a_{(anch)} \), \( b_{(anch)} \) and \( c_{(anch)} \) are the mutually perpendicular axes of the anchor stones placed on the bed. The velocity profile taken from each experiment is included in Appendix II, with each profile also displaying the von Karman-Prandtl equation, from which the shear velocity was calculated.

Other experiments were also conducted, such as experiments using the anchor stones ‘A2’ and ‘A3’, however not all were included in the experimental analysis. A full summary of the experimental regime is included in Appendix I, with reasons for the exclusion of these experiments. In most cases, exclusion was due to shaking of the camera, which arose from fixing the camera to a supply pipeline, which vibrated imperceptibly. Only during the processing of the footage did the shaking become apparent.
<table>
<thead>
<tr>
<th>Code</th>
<th>Number of Repeats</th>
<th>( Q ) (m(^3)/s)</th>
<th>( u^* ) (m/s)</th>
<th>( D_{50} ) (mm)</th>
<th>( D_{98} ) (mm)</th>
<th>( a_{(anch)} ) (mm)</th>
<th>( b_{(anch)} ) (mm)</th>
<th>( c_{(anch)} ) (mm)</th>
<th>( t_{\text{max}} ) (mins)</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>0.072</td>
<td>0.077</td>
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<td>0.086</td>
<td>4.2</td>
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<td>64</td>
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</tr>
</tbody>
</table>

Table 3-2 Summary of experiments
3.5.2. Flow Conditions

The different flow rates chosen for this experiment were based on Chin (1985) who observed the formation of armour layers using the same flume as the present study. Chin (1985) provided a platform from which further investigation into cluster formations could commence.

- The lowest flow rate (60 l/s) was not sufficient to transport enough of the bed particles to form clusters. This can be explained by observing the shear stresses of the experiment. The calculated critical shear stress for the average grain size was $\tau_{cr} = 3.75 \text{ kg/m}^2$ and for the $D_{80}$ was $\tau_{cr} = 4.761 \text{ kg/m}^2$ (Petit 1994; Shields et al. 1936). The measured shear velocity at this flow rate was $\tau_o = 4.9 \text{ kg/m}^2$, which can be expressed in terms of the critical shear stress as $1.3\tau_{cr}^*$ and $1.03\tau_{cr}^*$ for the $D_{50}$ and $D_{80}$ respectively. In their laboratory studies of uniform spherical particles, Strom and Papanicolaou (2002) observed that clusters form at shear stresses between $1.25\tau_{cr}^*$ and $2\tau_{cr}^*$. Comparison of these values with those for the present experiment indicates that the possibility of cluster formation lies at the lower threshold for cluster initiation if cluster formation is dependent on the transport of $D_{50}$ sized particles, and if cluster formation is dependent on the transport of particles coarser than the $D_{80}$, then cluster formation is improbable.

- The medium flow rate (66 l/s) transported enough of the bed load that clusters were able to form. The flow condition at this flow rate produced shear stresses of around $1.2\tau_{cr}^*$ for the $D_{80}$, which is within the expected range for cluster formation (Strom and Papanicolaou 2002a)

- The highest flow rate (72 l/s) was such that clusters could form, but the bed load transport was high and approaching the condition where all grains were in motion. Values of around to $2\tau_{cr}^*$ for the $D_{50}$ and $1.5\tau_{cr}^*$ for the $D_{80}$ were reached with these experiments. Considering $\tau_o$ in natural environments rarely exceeds $2\tau_{cr}^*$ and that the bed appeared to be unstable at flow rates higher than this, no higher flow rates were used

For the majority of studies, only the two higher flow rates (66 l/s and 72 l/s) were used. These two medium and high flow rates lay within the shear stresses under which clusters are known to form, therefore allowing optimal conditions for the observation of cluster formation.
3.5.3. Anchor Stone Placement

The difference in effect of two different artificially placed anchor stones on cluster formation was investigated at two flow rates. The anchor stones were of a similar a-axis dimension, but one was much flatter and elongate than the other (shorter b and c axes). Four other stones of similar dimensions to the elongate stone were used for the multiple anchor stone studies. The positions of these particles are shown in Figure 3-9.

Figure 3-9 Arrangement of anchor stones on test section, a) Plain bed, b) Anchor stone 1, c) Anchor stone 4, d) Multiple anchor stones
3.5.4. Grading Curves

Grading curves from the experiments conducted by Chin (1985) were imitated in this study. The majority of experiments were conducted using grading $G_1$ (Figure 3-10), which is the same as the sediment grading used in ‘Run 4’ of Chin (1985). This sediment grading was used to assess the effect of varying flow rate on the formation of clusters, and also to observe the influence of additional large anchor stones on the formation of clusters. Three other grading curves were used (Figure 3-10) to observe the effect of a bimodal bed on the formation of clusters. The grading curve $G_3$ is the same as ‘Run 3’ of Chin (1985). Grading curves $G_2$ and $G_4$ are not the same as any of Chin (1985)’s experiments, but are variations on $G_3$.

![Figure 3-10 Grading curves](image-url)
Chapter 3. Experimental Methodology
Chapter 4. Image Analysis Methodology

4.1. Introduction

The application of photogrammetry to the investigation of sedimentary processes has the potential to reveal new and useful insights. Photogrammetry is advantageous as it automates the analysis process, allowing in-depth investigation into vast quantities of data which would otherwise be time consuming.

The intention of these experiments was to observe the development of cluster formations under different conditions to provide a link between idealised laboratory experiments and field experiments. The use of natural gravels in the laboratory experiments provided a crucial stepping stone for the intensive observation of more natural formations. Experiments have been conducted for investigation into the development of cluster formations. The mechanics of local sediment transport during the period leading to cluster formation, during cluster existence and as the cluster disintegrates, were explored.

Photogrammetry was applied as the primary analysis tool in this investigation. Gravels painted according to their size were used to make particle identification easier (Figure 4-1). This novel technique required the development of a system for analysis of the images that were obtained. An analysis method was successfully developed to quantify the surface grain size distributions as they changed over time, track the position and orientation of individual particles over time and determine the position and geometry of clusters as they formed and disintegrated on the test section. This chapter describes the methods developed to obtain these photogrammetric tools and the philosophy behind the analysis procedure.

Figure 4-1 Painted gravels forming a cluster on a water worked bed
Chapter 4. Image Analysis Methodology

4.1.1. Introduction to Photogrammetry

Investigation into the motion of sediment particles in fluids has historically been a topic of great interest. The evolution of monitoring techniques has provided new insights which improve the base of knowledge in this field. Photogrammetry has emerged as a practical method for gathering detailed data from sedimentary motion (Moore 1976) and can be manipulated to provide in-depth information regarding the surface and particle characteristics of river beds (Keshavarzy and Ball 1999; Lane et al. 2001; Schuyler and Papanicolaou 2000). Photogrammetry is the study of photographs to determine quantitative information about a subject, and is well suited to the study of sedimentary processes as it is non-obtrusive and detailed. This type of monitoring requires detailed observation over prolonged periods of time (Keshavarzy and Ball 1999), and can be time consuming when done manually. Previous methods have relied on observation, sieving to determine surface sizes, and manual measurement of features on photographs of the test section to identify sedimentary features (Chin 1985). The automation of this process by using computers saves much time.

Photogrammetry can be applied to the test area either on the side of the flume, giving a profile view, or on top, giving a plan view. The side view allows measurement of multiple layers of grain movement but shows only the movement closest to the side wall. This method allows better identification of moving particles, as the grains move through water, and the plain background seen from the side view creates greater contrast with the entrained particle than a background of similar particles (Radice et al. 2006). The plan view shows movement over the entire surface of the bed; however in cases where sediment movement is deeper than one grain, not all movement is detected. Identification of the moving particles is more complicated as they are moving against a similar background, therefore contrast is reduced and detection more difficult (Radice et al. 2006). Painting of gravels is one way of mitigating this problem, and has been successfully done in other applications (Hassan and Church 2000; Wilcock and Mcardell 1993)

The accuracy of underwater photogrammetry can be limited by the distortions introduced by the water (Li et al. 1997). The water column has a refractive index 1.3 times that of air, which changes the focal length of the lens (Moore 1976). Calibration may be necessary to eliminate these distortions, and also those from relief, the lens or tilt (Butler et al. 2001a). Moore (1976) suggested a list of requirements for a camera in the use of photogrammetry. These are:

- rigid mount
• wide angle lens
• high resolution
• high metric accuracy
• large film storage capacity

4.1.1.1. Particle Tracking: PIV, PTV and DPT

Two other similar processes using photogrammetry in hydraulic engineering are PIV and PTV. Both of these technologies are widely and successfully used.

Particle image velocimetry (PIV) uses locally applied spatial correlation methods to obtain spatially averaged velocity vectors. Used for the tracking of seeded particles in a flow field to determine velocity, PIV uses knowledge of the mean flow field in its tracking method. PIV does not track individual particles, but local groups of particles and works best with heavily seeded flow (Keane and Adrian 1992). One method is the cross correlation method, which determines the position of a cloud of pixels, (the particle) then calculates the displacement and velocity vectors of the particle after identifying the most similar cloud density distribution in the consecutive image (Yamamoto et al. 1991). Particle Tracking Velocimetry (PTV) tracks individual particles in a flow field using consecutive frames in an image sequence (Nokes 2007), and works best with lightly seeded flow (Baek and Lee 1996).

PTV and PIV are used mostly in the study of fluid flows. In contrast, the primary goal of this research is to explore the sediment mechanics on the river bed. The study of sediment on the river bed presents different challenges to that of sediment suspended in fluid (Middleton et al. 2000). Saltating motion of sediment is stochastic, and cannot be predicted in the way that suspended sediment movement can be predicted. No existing tool was commercially available at the time of research; therefore, new analysis was necessary. A Digital Particle Tracking (DPT) program was written specifically for the tracking of the painted gravels used in these experiments. This tool for studying sediment motion on gravel bed-rivers was created in the present research. The development of the tool became a major aspect of this study.

4.1.2. Process Outline

For each experiment, an image was produced approximately every 1.5 s for approximately 5 hours, giving to up to 10,000 images per experiment. An example of a raw image of the test
Chapter 4. Image Analysis Methodology

section is shown in Figure 4-2 and a sequence of images extracted from a full experimental run is presented in Figure 4-3.

The process used for the complete photogrammetric analysis of clusters required initial calibration of the images, and then the images were sampled to digitally identify each coloured stone. Complete cluster analysis was achieved through the development of a boundary identification tool for observing clusters in a known location, a particle tracking algorithm tool and finally a cluster identification tool for locating and observing clusters as they formed and disintegrated on a bed as it was water-worked. Image processing for cluster identification was completed using the steps in Table 4-1, which are discussed in the following sections.

![Figure 4-2. Test section with coloured sediment: original, distorted image.](image)
<table>
<thead>
<tr>
<th>Process</th>
<th>Action (low frequency images)</th>
<th>Action (high frequency)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take raw images</td>
<td>Nikon (0.67 fps)</td>
<td>Video (30fps)</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>Processing</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>• Define threshold colour values</td>
<td>Define threshold colour values</td>
</tr>
<tr>
<td></td>
<td>• Calibrate or crop and rotate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rewrite 0.67 fps</td>
<td>Rewrite 0.067 fps</td>
</tr>
<tr>
<td>Image Analysis</td>
<td>Track (DPT) white particles</td>
<td>Track (DPT) all particles</td>
</tr>
<tr>
<td></td>
<td>• Track (DPT) red particles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Obtain surface grading curve</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Identify clusters as they form and disintegrate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Individual cluster analysis on selected clusters</td>
<td></td>
</tr>
<tr>
<td>Data Analysis</td>
<td>Combine cluster shape and position information with particle tracking data to analyse data</td>
<td>Sediment transport analysis</td>
</tr>
</tbody>
</table>

Table 4-1 Image analysis process
Chapter 4. Image Analysis Methodology
Figure 4-3 Sequence of images from experiment A0G1Q72
4.2. Image Calibration

Close range photography generally results in some image distortion due to the curvature of the lens. This shows in the image as either barrel or pin cushion distortion, the effect being exaggerated the closer the subject is to the camera. If being used for photogrammetry, a distorted image will yield inaccurate results and must be calibrated before analysis. Where distortion was noticeable in the images a calibration algorithm was developed to improve the images.

An image distortion equation was developed for one image in each experiment. Because the camera position was fixed for each experiment, the correction was then applied to the rest of the images. The image calibration process follows six steps:

1. Photograph the checkerboard grid in the test section
2. Create an ideal checkerboard in Matlab
3. Determine the coordinates of the corners of each square of the checkerboard images
4. Compute the distance between the coordinates of the photographed and ideal images
5. Interpolate to determine displacement required for pixels between points of known displacement
6. Re-plot the image with altered coordinates for each pixel

Step 1: Immediately prior to conducting the experiment a checkerboard was placed on the test section and photographed. After filling the flume to the depth at which the experiment would be conducted, the checkerboard was laid flat upon the submerged test section and photographed. The checkerboard was then removed, and without altering the position of the camera, the testing commenced. The camera remained fixed in place for the duration of the experiment.

Step 2: A checkerboard was generated on Matlab to use as an ideal undistorted reference image. The checkerboard was generated with the same dimensions and with the same number of squares as the checkerboard in Step 1.

Step 3: The corners of each square in the checkerboard were identified by finding the points where lines with a large intensity variation in the horizontal direction met with lines of large
Chapter 4. Image Analysis Methodology

intensity variation in the vertical direction. Coordinates of the corners were retrieved and placed in order.

Step 4: The coordinates of each corner in the photograph were compared with the corresponding coordinates of the same corner in the ideal image. The difference between the corners was recorded.

Step 5: To determine the displacement error in the pixels between the corners with known displacement a planar relationship was used for interpolation. Three corners of each check were used to estimate the displacement between the four points.

Step 6: A matrix of values showing the deviation of each pixel from the ideal straight grid was created in step 5. This information was used to alter the position of each pixel in a new image, creating an undistorted image.

Image calibration to remove distortion on the lens was conducted on images that showed visual distortion. All images that did not show visually identifiable distortion were not calibrated, and were simply rotated and cropped to the size of the test section.

Images were rewritten twice, once at the same frame rate as the original sequence, and the second time at 1/10 of the frame rate (0.067 fps). The low frequency image sequence provided a sequence that was much easier to manage and took less time to process, while still being frequent enough to capture cluster development and movement of the red particles, which happen over slower time frames.
4.3. Colour Separation and Surface Grading

Stream-bed armouring effectively changes the grading curve of the sediment on the surface of the bed, reducing the amount of fines on the surface and generally coarsening the sediment. Surface coarsening affects the surface layer of the sediment in three ways, the selective scour of fines, deposition of coarse particles, or the armouring to achieve equal mobility. The armour layer depth is considered as the depth to which a large surface particle ($D_{90}$) reaches (Bunte and Abt 2001). Often studies use the surface sediment of a sample to characterize the armour layer, due to the difficulties in obtaining a volumetric sample of constant depth. There are a number of ways to obtain a surface sample, which can be divided into three categories; pebble counts along transects, grid samples and areal samples. Pebble counts and grid samples are best applied in field situations. They can cover large areas by selectively sampling individual grains in a systematic manner, providing an unbiased overview of the sample size. Areal samples use either adhesive collection combined with sieve analysis or photography to collect the grain size of all particles within a predefined area and are applicable in both field and laboratory situations (Bunte and Abt 2001).

Photogrammetry was used in this study to measure this change in grading, allowing observation of the change in grading composition over time. Digital colour separation was required to isolate each different coloured particle in the images. This allowed analysis of individual size fractions. Colours were similar between runs, with slight variation due to lighting fluctuation.

4.3.1. Colour Threshold

When taking a photo, cameras have a sensor array where each individual sensor gathers information to create a pixel in the captured image. Photons fall into each pixel when an image is captured, with the quantity of photons determining the resultant light intensity of that pixel. To obtain a colour image, each pixel has a filter which allows only a certain colour to enter. The colours detected are red, green or blue. Single CCD cameras such as the Nikon D90 work using the Bayer array. The filtered pixels are arranged into a Bayer array, which has alternating rows of green-blue and green-red filters. The combination of red, green and blue intensity values for each 2x2 group of sensors is used to determine the overall colour for that pixel. The red, green and blue intensity information is available for each pixel, resulting in each image comprising of a length, width, and the red, green and blue (RGB) values for each pixel (Gonzalez et al. 2009).
Chapter 4. Image Analysis Methodology

The RGB intensity values for each pixel were observed, and the different colour combinations for each coloured rock were determined. As each colour has a distinctly different combination of RGB values, each colour group can be digitally isolated. The combinations of RGB values were identified for each colour using upper and lower threshold values and ratios between the three channels (Figure 4-4).

Figure 4-4 Colour isolation

4.3.2. Surface Grading Curves

Each image was analysed by the following algorithm (created using Matlab), containing four steps:

1. Equalisation of the colour saturation levels of each image
2. Definition of the colour ratio values for each coloured rock group
3. Isolation of each rock colour and calculation of the percentage of bed covered by the colour
4. Plotting of the percentage surface area coverage of each colour for each image.

Step 1: Using the Matlab function imadapthisteq.m each image was modified so that the contrast within the image is constant throughout the whole image, reducing the effects of changes in lighting and shadow around the image (Gonzalez et al. 2009).

Step 2: Separate different colours using their RGB values (Section 4.3.1)

Step 3: For each colour, the pixels with the RGB combination for that particular colour were placed in an individual matrix. This resulted in a new image being formed showing the rocks
that were painted that colour. The isolated monochrome rocks image was then converted into a black and white image showing the rocks as black silhouettes on a white background. The area covered by the black space in the new image represented the percentage coverage of that particular colour over the test bed.

Step 4: The percentage coverage for each colour in each image was then recorded. These values were plotted (Figure 4-5), resulting in a graph showing how the coverage of each colour changes over time.

Figure 4-5 is useful for demonstrating the general trend of particle movement with time. If armouring occurs, the plot will show a decrease in the percentage coverage of fines with time, and a corresponding increase in percentage coverage of larger particles. Instantaneous values can be extracted in order to create a grading curve, using the computed percentage of test area coverage for each of the five size groups as data points for the curve. This output required calibration to generate a traditional grading curve (Section 4.3.3)

The maximum surface coverage reached was 91%, due to shadows in the images, which reduce the detection of colours, particularly where the particles were coloured in darker shades.

![Figure 4-5 Surface grain size distribution over time](image-url)
4.3.3. Grading Curve Calibration

The unobtrusive nature of photographic analysis has made photograph assisted grain size evaluation popular, however most techniques measure the grain size of the particles once the image has been taken. This generates a number of issues regarding the compatibility of sampling method with the more traditional sieving methods. In particular, the two main issues in the calibration of typical photographic analysis are the underestimation of the axis lengths due to imbricated, submerged or hidden sections of particles, and varying volumetric conversion due to irregular particle shape (Bunte and Abt 2001). The method used in this thesis involved measurement of the grain size by sieving the sample prior to the experiment (and colouring according to particle sizes), then using the particle colours visible on the surface to show the percentage of each particle size on the surface. This method eliminates the problem of uncertainty in the measurement of grain size, however, still requires calibration if it is to be compared with grading curves taken using traditional sieve analysis, due to the difference in sample volume between the two methods (Kellerhals and Bray 1971; Proffitt 1980). The percentage surface coverage in this case is that of the 2D surface area of the visible coloured particles, as a percentage of the 2D surface area of the test section, whereas the percentage surface grain size using a sieve analysis of the surface grains is the percentage of each grain size relative to the volume of the top layer of the sample in the test section. To convert the surface area to volume, the surface area was multiplied by the average intermediate axis of the stone for each size fraction. An elliptical shape was assumed, and the mass calculated by an adaptation of the mass equation used by Bunte and Abt (2001)

\[ M_p = \pi \frac{A}{6} D_{50i} p_s \]  \hspace{1cm} (22)

where \( M_p \) is the particle mass, \( A \) is the visible surface area of the particle and \( D_{50i} \) is the median grain size of the \( i \)th size fraction.

Some differences between converted grain samples will still arise due to sediment characteristics and the penetration depth of adhesives. This is difficult to estimate as the depth is dependent on a number of parameters such as grain sorting, particle size, porosity and adhesive viscosity (Diplas and Fripp 1992). Calibration equations have been developed for this (Marion and Fraccarollo 1997); however without any information regarding the adhesive properties, which was wax in the case of Chin (1985), the necessary parameters to complete the equation are not available.
4.3.4. Surface Sampling

Different methods of surface sampling require calibration to be comparable to one another. In addition to the calibration required for the photographic areal sampling method (Section 4.3.3), calibration of these surface samples is required for comparison of the sample with volumetric samples (Figure 4-8). This is necessary in this study for the comparison of the surface grading curves obtained through image analysis, and the sieve samples obtained of the sub surface sediment. Although using an extremely simplified model, the thought experiment by Kellerhals and Bray (1971) clearly demonstrates this necessity. By observing a volume of tightly packed cubes with three sizes in equal proportions, Kellerhals and Bray (1971) compared the surface size distribution and volumetric size distribution of the cube. The resulting samples showed that surface sampling produced a biased result with a more coarse distribution. Kellerhals and Bray (1971) went on to propose that to convert a volumetric sample to an areal sample, the frequency of each size fraction should be multiplied by the grain size of that fraction ($D_i$) (Bunte and Abt 2001). In nature, sediment is
neither cubed, nor tightly packed and Proffitt (1980) predicted that the cube theory would create a bias in the measurement of natural sediment, causing a coarsening effect. Using experimentation with real sediment ranging from 0.2 mm to 38 mm, Proffitt (1980) proposed a conversion factor of $D_i^{0.47}$. Proffitt (1980) The application method of these conversion factors is enclosed in Appendix III. In Figure 4-9, the original subsurface grading curve obtained through mechanical sieving, the subsurface grading curve adjusted using the conversion factor from Kellerhals and Bray (1971) and that adjusted using the coefficient from Proffitt (1980) have been plotted, along with the initial surface grading curve obtained through photogrammetry. The coefficient proposed by Proffitt (1980) ($D_i^{0.47}$) under corrects the bias, creating a curve that is too fine. The calibration coefficient proposed by Kellerhals and Bray (1971), ($D_i$), also slightly under corrects the bias, however due to the tendency for fines to settle quickly during the placement of the bed, it is probable that this curve provides an accurate estimate of the subsurface grain size distribution.

Figure 4-8 Volumetric sample of the armour layer in comparison to a surface sample of the armour layer (Bunte and Abt 2001)

Figure 4-9 Calibration of a volumetric (subsurface) sample to compare with an areal (surface) sample
4.4. Digital Particle Tracking (DPT)

Particle tracking is useful in the determination of sediment behaviour on the bed surface. It has a number of other hydraulic applications including flow measurement, and non-hydraulic engineering applications, such as cell tracking in biophysics (Rogers et al. 2007). The tracking process contains three major steps (Capart et al. 1997):

- Particle identification
- Particle tracking
- Data organization and constructing velocity field representation from the individual particle trajectories

The identification and tracking of particles on gravel bed rivers has received minimal attention in the past, because it is a painstaking procedure to conduct without the aid of suitable technology. While particle tracking is relatively easy to do by eye, it is a slow and laborious task to conduct in any large quantity. Technological advances have assisted in making image analysis a popular method for investigating sediment transport (Heays et al. 2010; Keshavarzy and Ball 1999; Lane et al. 2001; Radice et al. 2006; Schuyler and Papanicolaou 2000). The use of coloured particles dramatically increases the likelihood of successfully tracking particles; the present project has taken advantage of this. The development of the sediment tracking algorithm requires a degree of understanding of the transport processes. Many individual particle movements were observed before the tracking algorithm was finalised. The following paragraphs present the findings from this work. An example video of the results of the DPT program in action is included in Appendix VIII-D.

4.4.1. Experimental Set-up Considerations

The following points were identified as being of importance when tracking particles:

- Resolution of image that is suitable for the subject being observed
- Frame rate fast enough to capture the degree of movement
- Enough variation in the bed colouring to enable detection of particles when displaced
- Bright colours to eliminate confusion with shadowed areas
- Lighting and contrast
- A stationary camera (and test section) to maintain a constant frame of reference
Successful particle tracking relies fundamentally on the acquisition of good quality images. The resolution of the image must be high enough that the smallest particle tracked is well defined. The image resolution required to perform particle tracking is primarily dependent on the size of the smallest particle to be tracked, and secondarily dependent on the features of the particle to be obtained when tracking. When tracking the larger particles (red and white) the analysis in this thesis retained high definition (> 200 pixels per particle) of the tracked particles to enable the measurement of the angle of the long axis of each particle, and detection of when each particle moved small distances.

The frame rate must be adjusted to match the movement of the particle being tracked. Large particles move less frequently and are fewer in number than smaller particles, making them relatively easy to track. Even at very low frame rates it can be possible to track particles if they do not move frequently and there are only a small number of them present at any one time. Smaller particles move much more frequently, and they are present in far larger numbers than large particles. This means that the tracking of smaller particles requires a fast enough frame rate to detect any movement, which is also complicated by the velocity at which these particles can move. A shutter speed that is not fast enough will capture only a blurry image of the particle as it moves, or scarcely detect the movement at all.

Variation in the bed colour allows the detection of particles as they move. If a particle is entrained and the particle beneath its original position is of the same colour, it can be almost impossible to distinguish between the two. This will result in the program not registering the entrainment, and a failed particle track. Ideally all of the particles would be of different colour, but this is impossible.

The choice of colour for the particles is important. While the colours must be suitably different from one another to be detected, the most important concern should be that the colours are bright. The use of dull colours and tones that include black is problematic. Darker colours are more likely to blend in with shadowy surroundings and should not be used.

Finally, lighting is very important. Without good lighting, it is impossible to get a good image, and tracking is difficult.

4.4.2. Particle Tracking Algorithm (Low Frequency)

Particle tracking can be conducted using one of two approaches, either through the recording of some or all of the positions of all the particles over time, or by the recording of any
movement that occurs. Generally the tracking conducted here was restricted to that of the movement only, this being mainly due to the conservation of time, reducing the number of particles that needed tracking. Also, this method is simpler due to the problem of particles appearing to merge when two particles of the same colour are adjacent.

The particle tracking algorithm was developed initially with reference to a particle tracking tutorial (Blair and Dufresne 2005) and a project report (Willacy 2008). These provided a sound basis for the construction of a program to track particles from a series of images. Substantial modification of the tracking algorithm was required to tailor the program to tracking sediment particles. This was undertaken using the program Matlab utilising observation and an iterative programming style. The particle tracking process used the following steps:

1. Read in image \(I_i\) and image \(I_{i+1}\)
2. Filter the image in order to observe only the desired colour
3. Subtract the images to determine movement
4. Filter the images to remove any noise and fill any holes
5. Obtain physical properties of all of the moved (entrained and deposited) particles
6. Compare the physical properties of the entrained particles with those that were deposited
7. Using threshold values and a likelihood weighting, assign the entrained particles to their most likely deposited pair
8. Record the tracking information and repeat the sequence for the next frame pair

Step 1: Because this algorithm works with image pairs, \(I_i\) and \(I_{i+1}\) must be loaded into the workspace. This allows comparison between frames to detect any particle movement.

Step 2: Isolation of the largest fraction of particles was achieved using the colour isolation algorithm, as discussed in Section 4.3. The resulting image was primarily blank, showing only the few largest particles in the test section. The image was converted to black and white.

Step 3: The fundamental process for the tracking of the particles was image subtraction, which can be used to identify any movement that occurs between frames. This is used where multiple, high frequency images, such as those obtained through video or automatic shutter photography, are recorded. In this analysis, sequential images were subtracted from one another as the movement of particles on the bed meant that the ‘background’ was
Chapter 4. Image Analysis Methodology

continuously changing. Both frames were loaded into the program, and the values of each corresponding pixel from the first frame were subtracted from those from the second frame. If the pixel values were the same in each image, the resultant was zero, indicating no movement between frames. If the pixel values were different between frames, the resultant was positive if the value in the first frame was higher than that of the second frame. With forward subtraction ($I_i - I_{i+1}$) using a black and white image, positive values indicate a particle has moved away from that position and negative values indicate a particle has landed in this position (Figure 4-10), thus providing a set of potential origins and destinations of the movement in the frame. These must be linked in order to successfully track the particles.

Step 4: Filtering was done by assigning a minimum size threshold, either the minimum expected particle size, or much smaller depending on whether the particles that shifted only small distances were included in the tracking.

Step 5: The physical properties of each moved particle were collected by using the stock Matlab command ‘regionprops.m’. Attributes collected were the $x$ and $y$ co-ordinate, size (pixels), particle orientation, major axis length and minor axis length.

Step 6: The particles detected to have been entrained in the first image were compared to those that were deposited in the second image. The linking of particle origin to destination
was achieved through the imposition of a number of thresholds. These thresholds were
developed through both simple logic and the extensive survey of particle movements, the
results being presented in Figure 4-11, Figure 4-12 and Figure 4-13. The survey was
conducted as an iterative process while developing the algorithm. Initially only the nearest
particle was assigned, but through the tracking of many particles, a more selective process
was developed.

A survey of 90 particle movements within 60 frames was compiled to aid the definition of
thresholds. The maximum $x$ displacement within this set of data was 983 pixels, equivalent to
about 600 mm and approximately $2/3$ of the test section. The relationship between
displacement and particle size (represented in pixels) was observed in order to define a
maximum $y$ displacement. Transverse rocking of particles meant that at small movements in
the streamwise direction, the movement in the transverse direction was likely to be
disproportionately large (Figure 4-11). With larger $x$-direction movement, where particles
actually entrained, generally the $y$-direction movement proportionately increased. For these
larger movements, the maximum $y$-displacement followed an upper threshold of $0.5x$.

The relationship between particle size and $x$-displacement was expected to assist in defining a
threshold for particle tracking. The survey shows a general decrease in the maximum size of a
displaced particle as the displacement distance increases. However, the trend is not defined
enough to form a definite relationship. A relatively unconstrained boundary condition was
developed for the maximum size, $A_{\text{max}} \leq 1400 - 0.5x$

The size ratio (area of particle in first frame/ area of particle in second frame) generally
remains at about unity (Figure 4-13), showing that change in size is less significant. A
threshold was applied of $A_{\text{max}}/A_{\text{min}} \geq 0.45$.

The particles were compared against a set of threshold values, as follows

- Forward movement only
- Displacement distance less than the maximum specified, this reducing as the particle size
  increases
- $y$ displacement is less than the maximum specified, this decreasing as $x$ displacement
  decreases until a minimum is reached at which point the maximum $y$ displacement is
  constant
- Particles are within the maximum and minimum specified size
• Difference between areas is less than the maximum specified, this reducing as the distance travelled increases

Particle pairs that conformed to these parameters were then given a compatibility weighting based on the following factors:

• Similarity of areas
• Similarity of major axis length
• Distance travelled
• Angle of direction of movement

![Figure 4-11 Stream-wise vs transverse displacement](Image)

![Figure 4-12 Relationship between particle size and stream-wise displacement](Image)
Figure 4-13 Ratio of entrained particle size to deposited particle size

Step 7: Once all potential pairs were assessed, the pairs with the smallest weightings were assigned to one another as a ‘track’ (Figure 4-14). Any stone in the following image that left from a similar position to that of the deposition of a previously tracked particle was assigned the same ID number as the tracked particle.

Step 8: The process was then repeated using the new position of the target particle as a starting point for the method. Each movement represents one change in position that was made by an individual particle within a 2 second interval. Results from the tracking provided information on the $x$ and $y$ position of the particle, particle area in the plan view, long and short axis dimension, and orientation and time of movement for any moved particle in the test section.
4.4.3. Continuous Particle Tracking

Particle tracking can be conducted using one of two techniques, either through the recording of some or all of the positions of all the particles over time, or by the recording of any movement that occurs. The largest fraction of particles on the bed, those that were painted red, were of small enough numbers that they could be tracked continuously. When larger numbers of the particles are present on the bed, the tracking of each individual particle...
becomes more difficult. With larger numbers of particles, both burying and overlapping of stones distorts the tracking history. During each experimental run, usually a period of approximately 5 hours, the observed particle would move in bursts downstream along the length of the section. The transport rate was very low, and many of the red particles would remain in place for the duration of the experiment.

The procedure for this experiment was fundamentally the same as that for the instantaneous tracking procedure described above. However, modification was necessary in order to ensure that the particle ID remained linked to the tracked particle while it was stationary. This was done by creating a window around the existing particle, placing that window over the second image and adding the contents of that window to the subtracted images (during Step 3). Thus, if the particle remained in place, it would show up in the subtracted image, and if it moved, the window would not contribute further to the subtracted image. The stationary particle would have the most similar attributes to its previous self, and therefore create a positive match. This system breaks down if another similar particle of the same colour is deposited into the position that the previous stone occupied, thereby rendering the image subtraction approach ineffective.

4.4.4. Particle Tracking of Smaller Particles (High Frequency)

The particles that were smaller than 9.5 mm were unable to be tracked using the Nikon images. Tracking of these particles required a faster frame rate than the 0.67 fps that was available using the Nikon D90. Video images were captured using the Casio EXILIM Pro EX-F1, providing frames at a rate of 30 fps, and image size of 1280 x 720 pixels. This was not used for all experiments, and was taken occasionally.

Particle tracking using video was also achieved using a similar process to that described in Section 4.4.2. The extremely fast frame rate made the tracking process much easier by shortening the distance a particle travels between frames. The grey particles were not tracked, because, they were too small and numerous to obtain a reasonable accuracy, given the frame rate and resolution.

4.4.5. Sediment Transport Rate Determination

Quantification of the sediment transport rate at any instant in the duration of the experiment is one advantage of using DPT. To remove any tracked particles which only shifted in place, but did not contribute to the sediment transport rate, only the sediment that moved further than
one particle distance was measured (Drake et al. 1988). Sediment dimensions are recorded in the tracking process, enabling computation of the plan surface area of the sediment. To calculate the volume ($\forall$) an assumption was made that the particle landed with its short axis vertical. Through a survey of particle dimensions, the short axis ($c$) was found to be on average $0.5a$. Using the volume of a spheroid:

$$\forall = \frac{4\piabc}{3} \quad (23)$$

where $a$, $b$, and $c$ are mutually perpendicular radii. Therefore, the volume of a sediment particle can be written:

$$\forall_{si} = \frac{\pi a_{si}^2 b_{si}}{12} \quad (24)$$

where the subscript $si$ denotes ‘sediment i’. Summing for all particles and converting to a sediment rate, gives the sediment load of the test section for any given time interval:

$$e_i = \frac{\rho_s}{\Delta t A} \sum \forall_{si} \quad (25)$$

where $e_i$ is the ‘areal aggregate sediment entrainment rate’ in g/m$^2$s, $A$ is the test section area, $\rho_s$ is the sediment density and $\Delta t$ is the time step over which the sediment volume is summed. The transport rate is expressed in unconventional units, ie g/m$^2$s rather than g/ms, to account for the sampling technique used. This transport rate, termed herein as the areal entrainment method, quantifies all movements on the bed and therefore, is scaled by both the channel width and the length of the test section.

Traditional sediment transport sampling uses a sediment trap downstream of a monitoring site, providing total sediment mass normalised by the stream width. This technique is also used herein, and is simulated by including only particles that are transported across a particular cross sectional line at a distance $x$ along the bed. This method is referred to as the ‘sediment trap’ method, the sediment load being given by:

$$q_{bx} = \frac{\rho_s}{\Delta t w} \sum \forall_{si} \quad (26)$$

where $q_{bx}$ is the ‘sediment trap’ sediment transport rate in g/ms and $w$ is the width of the test section.
4.4.6. Particle Tracking Accuracy

4.4.6.1. Low Frequency Tracking
In a 100 frame accuracy test, 99% accuracy was achieved for the red particles ($D_{98}$), and 88% positive detection and 1.5% false detection was achieved for the white particles ($D_{80} - D_{98}$), where positive detection is the correct track of a particle movement, and false detection is the incorrect tracking of a movement which may arise through an incorrect match, or the appearance of a false particle due to an error in the colour separation. This addition of false particles introduced the potential for the sum of the positive and negative detection percentages to equal greater than 100%. Random accuracy checks were frequently done to ensure the suitability of the tracking thresholds for each experiment. The performance of the tracking of the larger (red and white) particles was accurate enough to provide high quality data on the movement of particles under the chosen experimental conditions. Tracking accuracy was much reduced for smaller sizes due to their more dispersed nature and the 0.67 fps frame rate, which was too slow to capture a manageable amount of particles.

4.4.6.2. Continuous Tracking
The continuous tracking method achieved an extremely high accuracy (>99%) when monitoring using the number of particles successfully tracked per frame as a reference measure. As only the largest particles (> $D_{98}$) were tracked using this method, the high accuracy was due to the low frequency of movement of the particles. If the accuracy was measured using the percentage of moved particles that were successfully tracked, the accuracy would become similar to that of Section 4.4.6.1.

4.4.6.3. High Frequency Tracking
The accuracy of the video tracking was dependent primarily on the colour of the particle that was tracked. A 7 minute general survey was coupled with a 200 frame detailed survey to determine the accuracy of each colour when tracked. The white particles ($D_{80} - D_{98}$) were the most easily identifiable, and therefore had 98% positive tracking accuracy and 9% false tracks. The yellow particles ($D_{38} - D_{55}$) were also generally easily identifiable. However, due to their small size, at times they moved too fast to clearly be detected, therefore reducing tracking accuracy to 87%, with false detection of 8%. The green particles ($D_{55} - D_{80}$) were the most difficult to track as they were dark and did not show up well. They had 74% positive and 41% false detection. The red particles moved so infrequently that there was no
opportunity to track them in the videos on which the tracking process was conducted. The grey particles were not tracked.

The substantially higher frame rate exaggerates these error values. With DPT it is possible to miss a movement between frames for various reasons. With the relatively high frame rate, the potential for missed particle tracks increases. If this happens, the DPT program will interpret the missed particle track as one particle landing and another being entrained. This has an effect of shortening the perceived entrainment distances and durations. Steps were taken to mitigate this problem in the DPT program; however it is difficult to avoid if a number of tracks are sequentially missed. This effect is not such an issue at lower frame rates, because sediment is rarely in transit for longer than 2 frames. Because the sediment trap method only looks at one position along the length of the test section, this flaw does not affect that result in the same way, so that a particle will either be detected or missed.
4.5. Cluster Identification

Analysis of the behaviour of clusters presents the problem of defining the spatial boundary of the cluster. To achieve a reasonable definition, previous research was used. Strom et al (2008) conducted a field analysis to identify natural cluster formations and classify them into shape, their geometric properties and their spatial arrangement. In this study identification of clusters was done visually, using the broad definition of a cluster which is ‘a discrete organised grouping of particles that sits above the average elevation of the surrounding bed surface’. Clusters have been described as closely nested groups of particles aligned parallel to the flow (Brayshaw 1984). Brayshaw (1984) suggested that clusters generally consist of accumulations of particles, typically formed around an exceptionally large clast above the level of an otherwise planar bed. Hendrick et al (2010) used a broad definition when surveying a mountain stream for clusters, classifying a cluster as one or more clasts which impede the progress of two or more sediment particles and protruding above the normal gravel bed surface of the immediate surrounding area. They defined the surrounding area as the 50 cm radius surrounding the cluster, and imposed a size limit on the minimum anchor stone size as 5 cm, which was equal to the mean grain size in the study (Hendrick et al. 2010).

4.5.1. Philosophy

The use of photogrammetry enables automation of the survey process. For this to be done, the definition of clusters by others was taken into consideration and additionally, the philosophy that a cluster is more stable than the surrounding bed was used. This concept of stability was used to isolate the areas of the bed that were stationary over extended durations. Other factors influencing the automatic determination of what is or is not a cluster, were that the cluster was formed, i.e. particles moved into the cluster to form it, and did not already exist in position due to the initial placement of the bed, and that there were at least two stones in the cluster.

4.5.2. Removal of Moving Particles

The image analysis process used image subtraction between subsequent images to identify any moving particles between frames; these moved particles were then subtracted from the first image in the sequence. Figure 4-15 shows a selection of images from this process. Any moving particles were subtracted from the image, leaving only black spaces where they once
rested. Repetition of this process results in a mainly black bed, with only a small number of particles remaining in place; these are the stationary particles. If a cluster is to be formed, it is these stationary particles that will be involved in its formation. Figure 4-16 shows the progression of the percentage of the bed that remains stable after eliminating any area where particles are moving. Each line shows the percentage of stable area of one frame as the movements in the subsequent 60 minutes are subtracted from it. The figure shows that for the first few sequences, the stable area drops quickly down to around 30%, after 20 minutes the rate of erosion begins to level, and by 30 minutes the rate of erosion of the stable areas begins to stabilise. This demonstrates the tendency for the bed to consist of a large fraction of moveable sediment, and a smaller portion of stable sediment. Any clusters that may be present on the bed will exist in this stable section; therefore, the cluster identification process interrogates this remaining stable fraction for any unusually large groupings of particles.

For the analysis, the stage at which enough of the bed material is eroded away to show stable formations must be balanced with the stage at which the image is degraded too much due to light fluctuations, therefore darkening the image. The end stage was chosen based on around 10% to 20% of the bed remaining visible, and the reduction in removal of sediment having stabilised, determined by inspection of Figure 4-16. This value is dependent on the sediment transport rate of the experiment. The outlined elimination process was conducted for every 30th frame, approximately every 10 minutes, for the whole sequence of images. The 10 minute interval between detection sequences was chosen as a short enough duration, relative to the transport rate of the sediment, to detect any major changes in the bed. An example of the image subtraction process is included in video format in Appendix VIII-D. Firstly the erosion process is shown as a frame is eroded over 30 subsequent minutes, and then a video of the eroded images (every 30th frame) for one experiment is shown.
4.5.3. Cluster Identification

The images showing the stationary particles were then manipulated so that only the largest particles and groups of particles were shown (any particle size greater than $D_{80}$). Only the stable areas that were identified in at least two consecutive sequences were kept. These were
then labelled as clusters. Images taken from the cluster identification process are shown in Figure 4-17. Groups of particles identified between consecutive frames were said to belong to the same cluster if their centroids were less than 40 mm (maximum grain size) apart from each other. The image was ‘eroded’ to remove any small particles and enable identification of any large (white or red) particles that were adjacent to each other in groups larger than the average particle size. These groups were compared with those identified in the previous two sequences and only clusters that were at least partially present in one of the two previous sequences were considered to be clusters. The clusters were tracked between sequences to give a history of the cluster. An example video of the cluster identification process, applied to experiment AIG1Q66, is included in Appendix VIII-D.

Figure 4-17 Series of images showing cluster identification process, a) Original image, b) Eroded image, c) Red and black particles isolated, d) Groups larger than average particle size, e) and f) Clusters encircled by red ellipses
4.5.4. Cluster Identification Error

The difficulty in identifying clusters digitally has presented itself numerous times throughout this study. An example of the identified clusters at the end of experiment A0G1Q66 is shown in Figure 4-18. Figure 4-19 shows the comparison of the positions of the identified clusters with the surface elevation of the test section (taken at the cessation of the experiment). There is very good agreement between the position of the detected clusters, and the most elevated sections of the bed. Difficulty arises in determining the extent of the cluster, if based on elevation alone, the surface area of the cluster would be much greater. This is demonstrated by the dashed lines drawn on Figure 4-19 which show the approximate extent of the elevated bed area associated with each cluster. Surface elevation data were not available continuously for the experiment, so the cluster identification process does not take this into account. The clusters identified in this manner can be said to be the ‘core’ of the cluster.

Figure 4-18 Position of clusters detected in run A0G1Q66 near the end of experiment

Figure 4-19 Position of clusters on the surface elevation contour plot from run A0G1Q66 with possible extent of clusters outlines by dashed lines
4.6. Typical Cluster Monitoring

Because clusters can occur at any time, in any position on the river bed, their observation can be complicated. Hence, there were two aspects of cluster analysis, firstly, identification (section 4.5), and secondly, monitoring. Due to their more easily defined characteristics, and therefore greater potential for direct identification, typical clusters were targeted for more in-depth analysis. To observe the particle size distribution within the cluster, the Typical Cluster Composition tool was developed to provide a more detailed description of the boundary of the cluster and how it changes over time. Definition of the spatial boundaries of the cluster is difficult, particularly as photogrammetry in this case did not allow for the retrieval of 3D topographical data. Some simplification was necessary to automate the process.

4.6.1. Typical Cluster Composition

This was a simple process developed to determine the grain size distribution of the bed upstream and downstream of the anchor stone. Each red stone was considered as a potential anchor stone for a cluster. Using a similar ‘erosion’ process as that in Section 4.5.2, each experiment was examined in a time lapse style. A shorter lapse of 5 minutes was used for this process. After each 5 minute period of image erosion, a rectangular section upstream of the anchor stone was sampled in strips to measure the percentage of bed that remained stable. This was repeated for rectangles downstream, and to either side of the anchor stone. The upstream and downstream sample areas were the width of the cluster in the streamwise direction, and extended to 120 mm in length (equivalent to $4D_{100}$). At each time step, the program also allowed sampling of the grain size distribution (Section 4.3.2) of the bed surrounding the anchor stone. Any anchor stones that had 50% of the bed stable for a distance of $1.5D_{100}$ upstream of the stone were selected for observation as a potential cluster.
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4.6.2. Cluster Boundary Tool

To digitally determine the spatial boundaries of the cluster, firstly the side boundaries were assumed to be set at the edge of the anchor stone, as the high shear stresses on either side of the anchor stone discourage deposition in these areas (Brayshaw et al. 1983). Identification of the stoss and wake portions of the cluster was achieved through the assumption that any large particles directly upstream of the anchor stone were a part of the stoss, and any small particles directly downstream of the anchor stone were a part of the wake. Separation of the bed into different colours relating to the typical sizing of cluster components made this a relatively straightforward process. Any stoss particles or groups of particles, which were touching the upstream side of the anchor stone, were isolated and assumed to form the stoss. A similar process was used for the wake particles. Observations of these two areas provided details of the change in size and shape in plan view of the stoss and wake over the duration of the
experiment. The movements of any larger sized particles entering, leaving or influencing the cluster region were recorded for more in-depth analysis.

Figure 4-21. Cluster with stoss and wake sections identified, a) Original image, b) Cluster boundary identified
4.7. Application of the Analysis Process

Various tools were used on the images to extract detailed information about the cluster development. The results from these analyses produced large volumes of data regarding the time and position of the cluster. A summary of the tools used follows.

<table>
<thead>
<tr>
<th>Pre-processing tools (input: raw images)</th>
<th>Pre-processing outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration and cropping</td>
<td>Series of usable images</td>
</tr>
<tr>
<td>Colour separation</td>
<td>5 m-file function files (Matlab 2010b), one for each colour, for each experimental run</td>
</tr>
</tbody>
</table>

Table 4-2 Pre-processing tools

The pre-processing of the images produces an output of a series of images that are cropped to show only the test section, and are not distorted. The colour separation thresholding must be done on each set of images as lighting between runs can alter and change the colours slightly. The colour separation output is a function m-file for each colour of the bed, which when run produces an image showing only that colour.

<table>
<thead>
<tr>
<th>Processing tools (input: processed images)</th>
<th>Processing outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle tracking white stones (0.67 fps)</td>
<td>Data array of particle movement information</td>
</tr>
<tr>
<td>Particle tracking red stones (0.067 fps)</td>
<td>Data array of particle movement information</td>
</tr>
<tr>
<td>Cluster identification</td>
<td>Data array of cluster information</td>
</tr>
</tbody>
</table>

Table 4-3 Processing tools

The outputs generated from the image processing all contain information about the position, size, shape and orientation of the tracked particle or cluster. This information provides a story of the behaviour of the most significant elements in the river surface. Table 4-4 shows the typical output of a particle tracking analysis, where subscript $i$ refers to the identification number of the tracked particle, and subscripts $e$ and $d$ refer to whether the particle was entrained or deposited particle, respectively. Figure 4-22 shows the axis and orientation of the particle, it being assumed that the particle lies with its shortest axis vertical. Therefore the
long and short axes on the 2D image are the $a$ and $b$ axes. This neglects the effect of the angle of repose changing the effective width of the particle when observed from above.

<table>
<thead>
<tr>
<th>Time ID</th>
<th>$x$ coordinate</th>
<th>$y$ coordinate</th>
<th>Area</th>
<th>$a$ axis length</th>
<th>$b$ axis length</th>
<th>Particle orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$ (entrained) $i$</td>
<td>$x_{ie}$</td>
<td>$y_{ie}$</td>
<td>$A_{ie}$</td>
<td>$a_{ie}$</td>
<td>$b_{ie}$</td>
<td>$a_{ie}$</td>
</tr>
<tr>
<td>$t_1$ (deposited) $i$</td>
<td>$x_{id}$</td>
<td>$y_{id}$</td>
<td>$A_{id}$</td>
<td>$a_{id}$</td>
<td>$b_{id}$</td>
<td>$a_{id}$</td>
</tr>
<tr>
<td>$t_2$ $i+1$</td>
<td>$x_{(i+1)e}$</td>
<td>$y_{(i+1)e}$</td>
<td>$A_{(i+1)e}$</td>
<td>$a_{(i+1)e}$</td>
<td>$b_{(i+1)e}$</td>
<td>$a_{(i+1)e}$</td>
</tr>
<tr>
<td>$t_2$ $i+1$</td>
<td>$x_{(i+1)d}$</td>
<td>$y_{(i+1)d}$</td>
<td>$A_{(i+1)d}$</td>
<td>$a_{(i+1)d}$</td>
<td>$b_{(i+1)d}$</td>
<td>$a_{(i+1)d}$</td>
</tr>
<tr>
<td>$t_n$ $n$</td>
<td>$x_{ne}$</td>
<td>$y_{ne}$</td>
<td>$A_{ne}$</td>
<td>$a_{ne}$</td>
<td>$b_{ne}$</td>
<td>$a_{ne}$</td>
</tr>
<tr>
<td>$t_n$ $n$</td>
<td>$x_{nd}$</td>
<td>$y_{nd}$</td>
<td>$A_{nd}$</td>
<td>$a_{nd}$</td>
<td>$b_{nd}$</td>
<td>$a_{nd}$</td>
</tr>
</tbody>
</table>

Table 4-4 Tracking output

![Particle dimensions](image)

Figure 4-22 Particle dimensions
4.8. Limitations of Image Analysis

The precise nature of image analysis means that any small variation in the experimental setup will affect the processing. Therefore, in some cases it was necessary to adjust the images or make assumptions when processing the data.

4.8.1. Experimental Setup

All possible steps were taken to minimise the variation between setup conditions for experimental runs, however this remained an issue. The slightest change in conditions is detected in the image, and any differences between images will affect the image analysis process. The following issues were addressed during processing and the corresponding steps were taken to reduce the effects.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light fluctuation</td>
<td>Digitally adjust light balance on image during processing</td>
</tr>
<tr>
<td>Camera shaking</td>
<td>Attempt to minimise through the use of a steady camera support. If shaking was too bad, the experiment needed to be repeated</td>
</tr>
<tr>
<td>Battery replacement</td>
<td>Replace without changing camera position</td>
</tr>
<tr>
<td>Water on flow skimmer</td>
<td>Wipe water off skimmer and carry on</td>
</tr>
<tr>
<td>Bubbles under the flow skimmer</td>
<td>Attempt to minimise by diverting any bubbles to the sides of skimmer</td>
</tr>
<tr>
<td>Murky water</td>
<td>Re-run test once water is clear</td>
</tr>
</tbody>
</table>

With these measures it was possible to produce high quality data sets. However, quality control was always necessary both while conducting the experiment and during processing.

4.8.2. Adjustable Sediment Table

As noted in Section 3.2.2 the use of the adjustable sediment table enters a degree of uncertainty into the control of the experiment. The level must be controlled in response to the degradation of the bed, and this can only be done manually. To observe the effect of the adjustable sediment table on sediment transport, Figure 4-23 shows the sediment transport fluctuation (at minute intervals) over time with the adjustable sediment table level overlaid.
Chapter 4. Image Analysis Methodology

Encircled is a period of time with exaggerated sediment transport rate and a corresponding prolonged increase in adjustable sediment table. During experimentation, the relationship between these two factors can be blurred. The bed was raised to maintain the requirement for the upstream bed level to remain flush with the fixed bed upstream. However, it is possible that at times the raising of the bed forced higher sediment transport rates. Figure 4-24 shows the same comparison for a different run, for which the relationship between the bed level and the sediment transport rate is much harder to isolate. While the adjustable sediment table is bound to have influenced the sediment transport rate at times, the nature of sediment transport is so complex that it is difficult to isolate this effect. Care was taken to minimise these effects and in the remainder of this analysis, the effects of this are assumed to be negligible.

Figure 4-23 Comparison of sediment transport rate with adjustable sediment table level ($A6G1Q66$), red circles showing a period of high transport corresponding with a fast change in bed level
4.8.3. Processing

When automating a process as complex as cluster formation, it is necessary to make assumptions and generalisations. Taking aerial photographs of the bed provided only a 2D perspective of the bed mechanics. This places a limit on the accuracy of the cluster identification, as other studies have cited that the bedform should be raised above the average bed surface to be considered a cluster. Because this was not an option in this analysis, the cluster was identified according to size and stability.

The division of particle sizes to be painted was based on the size thresholds observed by previous authors that play significant roles in the cluster formation. The largest red particles act as anchor stones, the white particles form the stoss and the yellow and grey particles form the wake. The medium blue particles are not mentioned as playing a significant role in cluster formations. In practice, the roles played by the particles were not so clearly defined. In particular, many white particles played major roles in the initiation of clusters, and many blue particles formed a part of the stoss. When identifying clusters, only red and white coloured particles were considered; if the blue particles were included in the cluster search it would be difficult to isolate clusters, as the blue particles filled much of the space between clusters. Therefore, some clusters that were formed with the majority of blue particles are excluded in the identification of clusters.
Chapter 4. Image Analysis Methodology
Chapter 5. Digital Particle Tracking of Sediment Transport

5.1. Introduction

The nature of cluster formation is intrinsically reliant on the mechanics of the surrounding bed. Regardless of flow conditions and sediment properties, without selective transport, cluster formation will not occur. An understanding of particle movement can lead to insights into the formation of more coherent structures on the bed surface, such as pebble clusters, ribs and riffle pools (Malmaeus and Marwan 2002). Consequently, this research requires an understanding of the sediment transport mechanism of the test section. Sediment transport is inherently stochastic, dependent on the surrounding flow turbulence, and the stability and history of the immediate surrounding bed. Sediment transport behaviour is difficult to generalise, and sediment transport equations to date are not conclusive. The initial entrainment of grains has attracted extensive investigation over the past few decades and is still being studied in depth (Andrews 1983; Buffington and Montgomery 1997; Dwivedi et al. 2010; Mao and Surian 2010; Petit 1994). Similarly, bed load transport has been extensively researched, with questions still to be answered regarding the trends and processes behind particle movement (Diplas and Shaheen 2007; Raudkivi 1967). The relationship between sediment transport and the flow conditions, and the quest for an equation to relate sediment transport rates to the stream conditions, has been long pursued. If anything, research into sediment transport mechanisms has highlighted the variability and site specificity of sediment transport behaviour. When including the effect of clusters into sediment transport rates, there are both reduction and addition effects caused by particles being trapped into the cluster, and then released when the cluster disintegrates. The complex behaviour of sediment transport was investigated through the use of the Digital Particle Tracking (DPT) program that was developed for the study, which enables the sediment transport patterns to be monitored over time.

The quantification of sediment transport gained by using Digital Particle Tracking (DPT) provides a rare insight into the interaction sediment undergoes with the flow and with the rest of the bed. The behaviour of particles as they are transported can be quantified by allowing observation of individual particle movement. Observations from this are presented below. DPT was used in two formats, first to analyse the low frame rate data that were used for the
cluster formation research, and secondly to analyse video data obtained for an additional comparison using a higher frame rate.

The low frequency DPT was able to capture only the largest particles on the bed, those coloured red and white, and greater than the $D_{80}$ (9.5 mm). The 0.67s frame rate was too slow to record smaller particle movements with accuracy. The slower frame rate did however provide high quality images for up to 6 hours, detailing the entire bed.

High frequency DPT allowed tracking of all painted particles, providing information on all particle movements greater than the $D_{38}$ (2.8 mm) for the duration of the recording. The trade-off for this was that only 10 minute videos could be captured, and only a 300 x 300 mm$^2$ section of the bed could be monitored at high enough resolution to view the smallest particles.

This chapter presents the DPT results from high and low frequency image capture for experiment AIG1Q72. An experiment featuring a large anchor stone present on the bed was chosen to allow insight into the behaviour of sediment surrounding a large cluster. The results of the DPT provide extensive detailed information about the sediment behaviour on the bed. The challenge is a problem of how to arrange the vast quantities of information that are retrieved, rather than the original problem that Drake (1988) and others faced, that is the tedious task of retrieving the information from the images. Quantification of such detail in sediment transport would otherwise be difficult. The results shown here are an example of what can be achieved with the application of DPT to sediment movement and secondly as a description of the sediment transport behaviour under photogrammetry. Comparison between experiments and the behaviour of sediment transport is explored further in subsequent chapters, however only in relation to cluster formation. The wider field of sediment transport is a vast obstacle to hurdle, and while DPT could certainly be of use for improving that base of knowledge, the primary interest in this chapter is to present some of the more general characteristics of the sediment used in these experiments. In particular, focusing on the temporal and spatial patterns of entrainment with the ultimate aim to improve knowledge about cluster formation.

5.2. Average Sediment Transport Rate

The DPT results provide information on the movements of particles from which the sediment transport rate of the bed can be determined. As discussed in Section (4.4.5), this can be done
in two different ways; the areal entrainment method which sums the volume of all entrained particles from the bed, and the sediment trap method, which includes only those particles that cross a certain section along the bed. The areal entrainment rate and sediment trap method address two different aspects of sediment transport and have different merits; the sediment transport rate varies spatially throughout the bed, so the ability of the entrainment method to provide information over the entire bed is useful, particularly when observing the effect of clusters on the bed. The sediment trap method is comparable to existing methods, therefore producing values that may be compared with other study results.

A summary of the hydraulic conditions of the experiment, and comparison with the measured and theoretical fractional sediment transport rates, using the formula developed by Wilcock and Crowe (2003) is presented in Table 5-1.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Frame rate (fps)</th>
<th>(\tau_0) (pa)</th>
<th>(D_i) (m)</th>
<th>(F_i) (%)</th>
<th>(D_{sm}) (m)</th>
<th>(W_i^*)</th>
<th>(q_{hi}) (g/ms)</th>
<th>(q_{b=630}) (g/ms)</th>
<th>(e_i) (g/m²s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1GIQ72</td>
<td>0.67</td>
<td>6.25</td>
<td>0.017</td>
<td>28</td>
<td>0.007</td>
<td>0.026</td>
<td>0.021</td>
<td>0.0061</td>
<td>0.0302</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1GIQ72</td>
<td>30</td>
<td>6.25</td>
<td>0.017</td>
<td>28</td>
<td>0.007</td>
<td>0.026</td>
<td>0.021</td>
<td>0.022</td>
<td>2.61</td>
</tr>
<tr>
<td>high frequency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-1 Flow conditions, theoretical fractional sediment transport rates \((q_{hi})\), measured fractional sediment transport rates \((q_{b=630})\) and areal aggregate sediment entrainment rates for the high and low frequency experiments for grain size = 9.5-25 mm. Where \(\tau_0\) = shear stress, \(D_i\) = the mean grain size of the size fraction, \(F_i\) is the proportion of the bed surface covered by the size fraction, \(D_{sm}\) = the mean surface grain size, \(W_i^*\) is Wilcock and Crowe (2003)’s dimensionless transport parameter

5.2.1. Comparison of Theoretical and Measured Transport Rates

The comparison of measured and theoretical transport rates (Table 5-1) focuses on the average transport rates of the white particles \((D_{80}-D_{90})\), for which both low and high frequency information is available. Wilcock and Crowe (2003)’s equation was derived using experimental observations, using recirculated sediment. This allowed dynamic armour to establish, therefore differing from the static armour conditions in the present experiment. The calculated fractional sediment transport rate is higher, but of a similar order of magnitude as the measured fractional sediment transport rate from the low frequency experiment. The higher theoretical rate is likely to be attributable to the condition of dynamic armour in the Wilcock and Crowe (2003) study, which would be expected to generate higher transport rates.

The rate measured from the high frequency data is very similar to the theoretical value. This similarity is likely to have arisen from the time of video capture and the short video duration, where the 7 minute video was taken within the first 10 minutes of the experiment, when
transport is highest. The transport rate drops sharply within the first hour, making the average rate for the low frequency measurement experiment lower. The peak values of the low frequency data, obtained within the first 10 minutes of the experiment, are comparable to the rates measured in the high frequency data (Figure 5-1).

![Figure 5-1 Comparison of average measured sediment transport rate of particles > 9.5 mm from the high and low frequency footage](image)

5.2.2. Comparison of Transport Rate Determination Method

The average fractional areal aggregate sediment entrainment rate ($e_i$) is included in Table 5-1. These values show significantly higher values for the areal entrainment rate than the sediment transport rate. This is expected as the difference in transport rate evaluation method is substantial. The summation of the mass of all the particles entrained from the bed, as is the case with the areal entrainment rate, does not easily relate to the summation of the mass of particles passing a section of the bed. The distance and velocity travelled by each particle as it travels along the bed influences the areal entrainment rate, whereas the sediment transport rate is independent of these variables. The areal entrainment rate is most useful for displaying spatial variation in transport patterns, whereas the sediment transport rate is best for providing a measure of the degree of movement of sediment downstream.
5.3. Low Frequency DPT Results – Large Particle Tracking

The long term response of the bed under constant flow rate was observed. The majority of the 350 minute test was recorded, and DPT results for all but two short intervals are available for the largest size fractions of the bed ($i > 9.5$ mm). To give an idea of the amount of movement occurring on the bed, Figure 5-2 shows the track lines of all of the large particle movements that occurred over the duration of the experiment. This experiment contained a large anchor stone positioned in the centre of the test section, which is highlighted in red in the figure. Grain immobility was investigated by Wilcock and McArdell (1997). They calculated the active portion of each size fraction by observing photographs at different time steps in an experiment. A grain was considered to be active if the particle had completely moved outside its previous position. This philosophy was adapted in this experiment, where particles were only considered if they had moved a distance greater than their particle size (diameter). From the DPT results, only particles that moved greater than $D_{max}$ were included to eliminate particles that shifted but were not entrained.

The particle tracking program only detected particles that were both entrained and deposited within the test section, therefore eliminating any chance of detection of particles that moved from the test section to further downstream.

![Figure 5-2 Time lapse showing particle movements over the test duration (large anchor stone circled in red)](image)

5.3.1. Sediment Transport Rate Variation with Time

In order to determine a suitable position at which to measure the sediment trap transport rate over time, the sediment trap method was applied at 5 positions along the length of the test...
section; these rates are averaged over the duration of the test and are presented in Figure 5-3. Position \( x = 630 \) mm was chosen as a good example of the peak transport rate; it is far enough along the test section for the sediment transport rate to be fully developed but not so close to the end of the section that entrained particles leave the bed and are not detected, falsely lowering the transport rate. The DPT was applied every 1.5 s giving a virtually continuous record of particle movement. The sediment transport rate of the particle movements was quantified every minute, providing a moving tally for the test duration, allowing observation of the temporal variation in transport rate (Figure 5-4). Figure 5-5 also shows the temporal variation in transport rate, calculated using the areal aggregate sediment entrainment method. Both figures show that the initial sediment transport rate drops quickly within the first hour of the experiment. The overall rate of transport continues to diminish for the remaining 5 hours, however it fluctuates greatly. Sharp peaks showing instantaneous increases in rate occur frequently throughout the duration of the test, as well as extended increases in transport rate lasting for up to an hour (Figure 5-4, \( t = 130 – 220 \) minutes and Figure 5-5, \( t = 130 – 180 \) minutes). While still fluctuating, the sediment transport rate in the last hour of the experiment is small, and punctuated by fewer and smaller peaks than earlier in the test. The test section is clearly in a transition zone for the duration of the experiment. The overall reduction in the sediment transport rate, coupled with the fluctuating load, shows that the estimation of an overall sediment transport rate for each experiment is insufficient to describe the dynamic nature of the bed at any instant in time.
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Figure 5.3 Average sediment transport rates at cross sections of the bed using the ‘sediment trap’ method of calculation.

Figure 5.4 Sediment transport rate per second at x = 630 mm using ‘sediment trap’ method of calculation (shaded areas are gaps in data collection).
5.3.2. Spatial Variation of Sediment Transport

Figure 5-6 shows the spatial distribution of sediment entrainment averaged over the 6 hour duration of the experiment using the areal aggregate sediment entrainment method of calculation. The larger anchor stone that was on the bed is identified by a red circle. In comparison to Figure 5-5, instead of showing the variation of transport rate with time, Figure 5-6 shows the variation of average transport rate over the test section. The process for creating the map was to divide the bed into 50 mm x 50 mm squares. The squares were chosen to be large enough to represent general trends while still dividing the bed into sections small enough to show spatial variations. The sediment transport map shows that sediment transport is concentrated in areas up and down stream of the large stone in the centre of the bed. Entrainment of the particles occurred primarily toward the centre of the channel, but was skewed to the left hand side of the channel centreline alongside and downstream of the anchor stone.

Using the sediment trap method, Figure 5-7 shows the variation of transport rate along the length of the test section, and shows how that distribution changes with time. Transport within the first hour is substantially higher than the remainder of the test, as shown in Figure 5-4 and Figure 5-5. Figure 5-7 reveals that the transport rate during the first hour is highest at the middle and downstream sections of the bed. Subsequent rates are all lowest at the upstream end of the bed and higher at downstream end of the bed. This conforms to the expectation that sediment will entrain from the upstream end of the bed first as the slope of the bed rotates (Chin 1985).
5.3.3. Sediment movement frequency

To investigate the frequency of particle entrainment, the interval between consecutive particle movements was recorded. This is displayed in Figure 5-8, with the main histogram showing all particle movements with the data divided into bins of 10 s, and the inset showing only the consecutive particle movements with intervals of less than 60 s (presented in bins of 1 second). The most common time interval between particles is between 0 and 1 second, but this can range up to 300 seconds. The average time between movements was 14 seconds. These results suggest that particle movement occurs in patterns, where particles are more likely to move when other particles are moving.
5.3.4. Distance Travelled by Sediment

The distance travelled by a particle for different particle sizes is presented in (Figure 5-9), which shows that the distance travelled is not always a function of particle size, as one might expect. An envelope can be fitted around the data, which shows that the maximum distance travelled by each particle size does decrease with increasing particle size. The overall average taken of particle movements shows contradicts this due to the majority of particle movements occurring at smaller sizes, with an initial increase in distance travelled as the small particles increase in size. A simulation of particle movements was conducted by Malmaeus and Marwan (2002) where particle movements were generated using a number of rules, based on the expected behaviour of particles. Their results show a similar, but more exaggerated trend, where larger particles travel smaller distances and smaller particles travel longer distances and show a relatively bimodal trend, where none of the larger particles travel distances remotely close to those travelled by smaller particles. It can be seen from Figure 5-9 that shorter distances are travelled more frequently and smaller particles are more likely to do so than larger ones. However, this also correlates to the size grading, where there is a larger proportion of smaller particles available.
5.3.5. Particle Orientation

Data obtained from the DPT process also included the orientation of the particle, where the particle shape was simplified by an ellipse encompassing the particle. The orientation of the particle is the angle between the x-axis (streamwise direction) of the image and the major axis of the ellipse. Due to the symmetry of the assumed elliptical shape, this angle ranges only between 0 and 180 degrees. The determination of the angle of orientation was done using the Matlab command ‘regionprops’, with the input command ‘orientation’ used from the image processing toolbox.

The detected particles were separated by distance travelled into two groups; those which travelled less than 20 mm and those which travelled more than 20 mm. This is to differentiate between particles which remain in place but are shifting or rotating slightly, and those which actually travel a distance. The orientation of these groups both before and after movement is presented in Figure 5-10 and Figure 5-11. Figure 5-10 displays the orientation of particles as they move but remain in position. The orientation that is detected is the orientation of the crescent that shifts. Therefore, if the particle wobbles in the transverse direction, the crescent orientation will be streamwise. Both plots show that the primary orientation is in line with the
direction of flow, such that when wobbling, particles are most likely to wobble in a direction transverse to the flow.

Figure 5-11 shows the orientation of the particles before and after they are entrained. These diagrams show that more of the particles are transverse to the flow than in line with the flow, which supports the observations made by some authors that the most stable orientation of a particle is that where its major axis is transverse to the flow (Keshavarzy and Ball 1996a). In order to add detail to this process, a higher frame rate must be used. The current rate of 0.67 fps gives only an image of the particle either prior to entrainment, mid-flight or after deposition. A higher frame rate would allow insight into the rotation process before and after landing.

Figure 5-10. Orientation (degrees) and number of shifting particles (distance moved less than the maximum particle diameter), a) Prior to movement, b) Subsequent to movement
Figure 5-11. Orientation (degrees) and number of entrained particles (distance moved greater than the maximum particle diameter), a) Prior to entrainment, b) Subsequent to deposition
Chapter 5. Digital Particle Tracking of Sediment Transport

5.4. High Frequency DPT Results

The behaviour of sediment was monitored using 30 fps video recording over a short period of time. The first 7 minutes of sediment movement after the maximum flow rate was reached was recorded. The video recording area was a section of the total test bed, Figure 5-12. The experiment was a repeat, with all conditions the same as those in AIG1Q72. The DPT detected all moving coloured particles that were painted ($i > 2.8$ mm) providing particle movement information every $1/30^{th}$ of a second. To demonstrate the nature of the results gained, an image sequence showing the DPT results in the form of quiver plots, is given in Figure 5-13. The black arrows represent the green particle movements that were detected on the bed, with each image showing the particle movements in 1 minute.

![Figure 5-12 Section of test bed observed by video recording](image-url)
Figure 5-13 Sequence of 1 minute long time lapse images of blue/green particle movements detected using DPT (scale with reference to the whole test bed). Each arrow shows the position, direction and relative velocity of a particle as it moves between frames.
5.4.1. Sediment Entrainment Frequency

The rate of sediment transport is known to change over time for a static bed such as this. Not only does the sediment transport rate diminish over time as armouring occurs and the bed approaches equilibrium, but the transport rate also fluctuates on a much smaller time scale due to changes in the flow intensity. The frequency of particle movements per second over the 7 minute recording period is shown in Figure 5-14 where the data are coloured according to the particle size. Figure 5-15 shows the same data, however any particle movements that travelled a distance less than the maximum particle size (25 mm) have been removed. Comparison between these two figures shows the smaller particles primarily travel distances less than 25 mm. This figure also indicates that particle movements made by large particles are accompanied by numerous movements by smaller particles.

The sediment transport rate can also be determined from the high frequency data using either the sediment trap method or the entrainment method. Results using the sediment trap method are given in Figure 5-16 and Figure 5-17. The distribution of sediment transport along the length of the observation window is shown in Figure 5-16, which also shows the rates of transport for different particle sizes. The transport rates are fairly constant along the length of the bed, other than a peak in the green and yellow particle transport rates at x = 580 mm. This might have been due to the presence of the large anchor stone creating isolated high shear velocities along the particle flanks, causing an increase in entrainment, however, a larger or longer observation window would be necessary to explore this further. The variation in transport rate over time at the position x = 480 mm is shown in Figure 5-17. Because of the short measurement time, no long term trends are observable in this plot. There is a period of increased transport during the last two minutes of recording, with a large fluctuation in peak rates.

The sediment transport rate calculated using the areal entrainment method is shown in Figure 5-18. While on a different scale, the patterns and peaks in transport are very similar to those in Figure 5-17. The fluctuation in transport rate is apparent, showing that sediment transport occurs sporadically. This pattern can also be compared to the longer time scale monitoring of the large particles in Figure 5-5, where a similar random oscillation of particle movement frequency can also be seen.
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Figure 5-14 Frequency of particle movements per second over time

Figure 5-15 Frequency of large movements ($\Delta d_{xy} > 25$ mm) over time
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Figure 5-16 Sediment transport rate (calculated using sediment trap method) at positions along the length of the observation window, showing the division between size fractions.

Figure 5-17 Sediment transport rate variation with time at x = 480 mm (calculated using the sediment trap method).
5.4.2. Fractional Sediment Transport Rates

Figure 5-19 shows the total sediment transport rate and the transport rates for the different particle sizes. The data, which were analysed using the sediment trap method, have been averaged using a 10 second moving window. The transport rate is generally highest for the smallest size (yellow particles), and lowest for the largest size (white particles). Information on the fractional sediment transport rate is relatively arbitrary without reference to the proportion of the bed that constitutes that fraction. If the majority of the bed comprises a certain particle size, it is probable that that fraction will produce the highest transport rate. To account for this, Figure 5-20 shows the fractional transport rates scaled by the percentage of bed comprised by that respective fraction (5%, 15% and 60% for yellow, green and white stones respectively). This changes the transport rate of the different size fractions dramatically, making the yellow particles most frequently entrained for the majority of the observed period and the white particles the least frequently entrained.

Detailed observation of fractional sediment transport rates has also been conducted using a coloured sediment bed by Wilcock and McArdell (1993; 1997). Their data have been used to provide a comparison to the data from the current experiment. The relationship between the average fractional sediment transport rates is plotted against the fractional surface grain size in Figure 5-21, where the transport rates are scaled by the available size fraction on the bed surface. The results from the high frequency data set are compared with two data sets from the Bed of Many Colours (BOMC) experiments by Wilcock and McArdell (1993). The conditions of the three data sets are presented in Table 5-2. BOMC4 was chosen as the experiment with the most similar dimensionless shear stress, and BOMC1 was the experiment
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with a total sediment transport rate similar to that of the present experiment. While it is difficult to compare experiments run under different conditions, the BOMC experimental runs are included to provide an indication of the expected trends. The shape of the transport relationship with sediment size is similar for the BOMC experiments and the present experiments; however the present experiments have much lower transport rates. Differences in experimental setup, the fact that the present experiment used a static bed and the BOMC experiments used live bed conditions, as well as the different sampling method make differences between the curves likely.

The curves show that transport rates decrease with increasing grain size, and after the grain size reaches a certain size, the gradient of the decrease changes. The results from this experiment partially verify the observation by Wilcock and McArdell (1993) that for smaller grains, the sediment transport rate is virtually independent of grain size, and transport is only dependent on the proportion of sediment available on the bed surface and the total transport rate. This graph indicates that the transport rate of the two smaller size fractions, when scaled by their available size fraction on the bed become approximately constant. The green and yellow particles do not display completely equal transport, as can be seen in Figure 5-20, where the yellow particles show consistently the highest transport rate for the majority of the time, however there is a significant change in average particle size between the two groups. The division between size independent transport and size dependent transport may lie at a particle size that is finer than the division between the green and white particle colours that were chosen in this study. Dividing the bed into smaller size fractions and observing the smallest sizes on the bed would improve the ability for comparison between these two studies. A decrease in transport for larger grain sizes may be attributed to a smaller entrainment frequency for coarse grains or to a size-dependent difference in the velocity or displacement length of larger particles.
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Figure 5-19 Sediment transport rate at x = 550 mm (calculated using the sediment trap method) averaged every 10 s showing the division among size fractions

Figure 5-20 Fractional sediment transport rate at x = 550 mm (calculated using the sediment trap method) averaged every 10 s showing the division among size fractions
5.4.3. Entrained Particle Velocity, Travel Distance and Sinuosity

The high frequency data provided information on the flow path of entrained particles, enabling evaluation of their velocity, distance travelled and directness of route. Particle velocity has been measured in the past, where Drake et al (1988) observed that, on average, larger particles were 30% slower than smaller particles. Shown in Figure 5-22, the particle velocity is shown with respect to particle size. The variation in velocity with particle size is summarised in Table 5-3, where it can be seen that in general smaller sized particles reached the highest velocities. Very small particles were subject to patchy detection, hindering the
accurate calculation of their velocity, and explaining why they highly represented in the slower velocities. The primary mode of motion for large particles was rolling and hence they were often slowed by contact with the bed, which explains their lower velocity.

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>Median</th>
<th>Variance</th>
</tr>
</thead>
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</tr>
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<td>0.457</td>
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<td>0.0369</td>
</tr>
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<td>1.47</td>
<td>0.545</td>
<td>0.504</td>
<td>0.0804</td>
</tr>
</tbody>
</table>

Table 5-3 Summary of velocity parameters varying with particle size

The distance travelled by particles is shown in Figure 5-23, where the majority of the particles are small, and only move small distances. The maximum distances were travelled by medium sized particles, however a longer observation time and larger observation window would be necessary to determine any pattern, considering only a handful of the larger particles moved in this period and that particles can move for distances greater than the observation window.

The other characteristic of entrained particle motion that was observed was the sinuosity of particle motion. The sinuosity was determined as the ratio between the total distance travelled by an entrained particle and the absolute distance travelled. This was relatively easy to calculate given the level of detail available in the video recording. An example of the different degrees of sinuosity is shown in Figure 5-24, while the relationship between sinuosity and particle size is shown in Figure 5-25. Significant sinuosity occurs only for in particles with less than 5 mm diameter. Particle sinuosity arises from the smaller particles being diverted around larger particles and being entrained into recirculation zones of particles large enough to create one. Larger particles are less susceptible to the transverse flow forces, and are likely to be of similar size or larger than particles that would cause disruption to smaller particles. Larger particles, if entrained, are more likely to simply stop when colliding with another large stone, or roll over the top (Drake et al. 1988), whereas small particles will be carried with the flow around the particle. The particles with extremely high sinuosity values can be explained by particles that were shifted slightly or wobbled by the flow but ultimately did not travel very far.
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Figure 5.22 Particle velocity of particles that moved > 25 mm

Figure 5.23 Distance travelled by particles according to particle size
5.4.4. Particle Movement Patterns

When large numbers of particles are entrained, their movements tend to be isolated to sections of the bed, with the remainder of the bed containing only relatively few particle movements. Figure 5-26 shows a sequence of images with all particle tracks that occurred over the period of 1 minute in each image in a time lapse style. The tracks are coloured according to particle size. This shows quite clearly the spatial and temporal variation in the particle movements on the bed.

Drake (1988) identified phenomena in sediment transport that led to the frequent, brief, localised, random sweep-transport events of high entrainment and transport. These events were estimated to last between 1-2 s and are most likely related to near bed turbulence events.
Chapter 5. Digital Particle Tracking of Sediment Transport

(Drake et al. 1988). A similar phenomenon was observed in the present study, where some particles obviously were entrained in response to turbulence events, and therefore were entrained in groups. Investigation into near bed, instantaneous shear stresses have found them to be significantly larger than average shear stresses by approximately 1.4 times (Keshavarzy and Ball 1996a). The instantaneous stresses acting on a particle are therefore higher than the average shear stress, enabling particle entrainment (Keshavarzy and Ball 1996b). This phenomenon is considered to be largely responsible for the stochastic nature of sediment entrainment, and may also be responsible for the entrainment of groups of particles such as the localised events noticed by Drake (1988).

Similar ‘localised’ events to those described by Drake (1988) were also noticed in this study. Isolation of these events was achieved firstly by observing video records to estimate the approximate spatial and temporal limits within which the events occurred. Particle movements were digitally sorted by grouping movements that occurred temporally within 1/6 second of the previous movement and spatially within 10 mm in the transverse direction of the bed of the most recently moved particle in the event. Figure 5-27 shows an example of two isolated localised events, one starting from the top left corner of the frame, and the other stating from the centre. Many of the particle movements appeared to occur in this manner.

Approximately 30% of all particle movements that were recorded occurred as a part of a localised event, which is much less than the 70% observed in field observations by Drake et al (1988). Figure 5-28 shows the rate at which particles are entrained in localised events over time. Figure 5-29 shows a comparison of the number of particles entrained in localised events compared to the total number of particles entrained. The relationship between the two values indicates that there may be a relatively constant ‘baseline’ of particles that are entrained at a lower and constant rate. Accordingly, the particles entrained in the sweep events appear to be the major contributors towards fluctuation in the rate of sediment transport.

Of the events that were identified, the maximum duration was less than 1 minute, with the majority of events lasting for less than half a minute. The relationship between event duration and the number of particles entrained is shown in Figure 5-30. Longer event durations loosely correspond to higher numbers of entrained particles with up to 80 particles entrained in a single event.
Figure 5-26 Particle movement pathlines over minute long time lapses, showing colour according to particle size, with dark blue and black tracks for smaller particles and lighter blue, yellow and red for large particle tracks.
Chapter 5. Digital Particle Tracking of Sediment Transport

Figure 5.27 Example of a localised entrainment event

Figure 5.28 Sediment transport rate (entrainment method) of particles showing the total rate and the rate entrained in ‘localised events’

Figure 5.29 Comparison of particles entrained in localised events, those not entrained in localised events and the total entrained particles
Figure 5-30 Number of particles in localised events according to the event duration
5.5. Conclusions

This chapter displays the results obtained from a Digital Particle Tracking (DPT) algorithm, which was used to analyse 6 hours of images of the evolution of an artificially created river bed, while being water worked and an additional 7 minutes of footage of high frame rate video of the bed. Only the larger size particles were analysed in the low frequency footage, and all painted particles were analysed in the high frequency footage. Data collected from the particle tracking included the x and y position of a particle before and after displacement, particle size, major and minor axis details, orientation and the time at which movement took place.

The temporal and spatial patterns of entrainment of an individual experiment were explored, as a precursor to the study of the interactions of sediment with clusters. The sediment transport rate was quantified using two different methods. Firstly the areal entrainment rate ($e_i$) was introduced, which is a measure of the quantity of particles as they are entrained (g/m² s). In this method, the entrained particles have a mass and position, where the entrainment rate for the bed may be found by summing the mass of all entrained particles at any moment, or the entrainment rate of a specific location may be found by only observing that position. This method has potential as an application for studying the spatial distribution of sediment entrainment. The second method was comparable to existing sediment transport measures. The ‘sediment trap’ method measured the mass of sediment passing a position along the length of the bed (g/ms), and could be measured and compared to other measurements of sediment transport rate. A comparison of the DPT sediment transport rates with theoretical rates calculated using the fractional transport rate proposed by Wilcock and Crowe (2003), showed the measured rates were within the same order of magnitude as the theoretical results. Slightly lower measured fractional transport rates for the low frequency DPT were attributed to the static bed conditions, and much higher measured transport rates for the high frequency DPT were attributed to the relatively early time of recording.

Results from the sediment transport measurements show that spatial variation of transport is high. Overall, sediment tends to be removed from concentrated areas on the test bed, particularly from the central test section, offset from the flume walls. Entrainment was initially highest in the upstream half of the test section, and then shifted further downstream as the armour layer formed and the bed rotated. Temporal variation in the sediment transport on the bed was apparent over the duration of the experiment. The rate diminished quickly
within the first hour of testing and then more steadily over time. Fluctuations in transport rate are apparent on the second, minute and hour scale, with large deviations from the time averaged values.

The frequency of particle entrainment was on average 1 movement every 14 s for large particles, however the most common time interval between entrainment of large particles was less than 1 second, suggesting that particles are most likely to move as other particles are moving. Smaller particles also follow this trend, where numerous smaller particles are likely to be entrained at the same time as individual larger particles. Investigation of the temporal and spatial relationship between particle movements at high frequency showed that 30% of particle movements occur in localised events that involve other nearby particles.

Travel distance of particles is limited by particle size, where larger particles travel the shortest distances. The longest distances were travelled by small and medium sized particles. The sinuosity of the travel path affects the distance that smaller particles travel. Particles small enough to be diverted around larger particles or entrained into the recirculation zone of larger particles could be diverted into pathways 20 times longer than the streamwise distance that they ultimately travelled.

Observation of the orientation of the a-axis of particles before they are entrained shows that they most frequently have their long axis transverse to the direction of flow, as is consistent with other studies. When particles wobble, but are not entrained, they tend to wobble transversely to the direction of flow.

The fractional transport rates of the smaller size fractions was dependent on the transport rate and percentage of that size fraction available on the bed surface and larger fractions showed diminishing transport rates.

These results show the ability for DPT to provide information on the behaviour of sediment transport in detail throughout time and space. This is a useful tool for the investigation into cluster microforms. Using varied experimental conditions or by coupling the study with unobtrusive velocity data acquisition, the tool has the potential to generate further insights into sediment transport behaviour.
Chapter 6. Armouring

As the formation of clusters has been found to play a significant role in the armouring process (Chin 1985), an understanding of the armoured surface is important. The experiments in this study were conducted with the aim of reaching an armoured equilibrium, and the observation of cluster formation was conducted during the evolution of the bed toward this point. The continuous photographic monitoring allowed quantification of the surface grain size at any point in time, over the duration of each experiment. Topographic surface profiling was also taken prior to, and at the conclusion of, each experiment.

Chin’s (1985) study of armouring provides excellent detail of the surface grading of a naturally armoured bed. The experimental conditions in the present study were designed to replicate Run 4 from Chin’s (1985) study. Under the same sediment grading and experimental setup, it was possible to compare the armouring of these two sets of experiments. A statistical investigation of the grain scale attributes of the armoured surfaces of the experiments was also undertaken, using Probability Density Functions (PDFs) and structure functions, which have been used to study numerous physical and geophysical phenomena under the term ‘variogram’ and have only recently been adapted to the statistical investigation of gravel bed roughness characterisation (Nikora and Walsh 2004; Nikora et al. 1998)

A summary of the $D_{50}$ and $D_{98}$ grain sizes of each experiment, the standard deviation ($\sigma$), Skewness ($S_k$) and Kurtosis ($K_u$) of the PDF of each experiment and Hurst exponent ($H_x$) from the structure function of each experiment are presented in Table 6-1. Each of these parameters are explained and discussed in the following sections, with Section 6.2 focusing on the grain size distribution, Section 6.3.1 focusing on the PDFs of the experiments, and Section 6.3.2 focusing on the structure functions. In addition to this, the depth of erosion and visible bed stability are also be presented in Section 6.1 and Section 6.4 respectively.
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Table 6-1 Statistical properties of the initial (screeded) and final (water worked) surface elevations of the test section
6.1. Depth of erosion

Comparison of the depth of erosion of the bed, measured as the change in level of the adjustable sediment table, is shown for the $G1$ grading curve at various $u^*$ compared with Chin (1985)’s study using the same grading curve (Figure 6-1). The depth of erosion increases rapidly at the start of the experiment, and asymptotically approaches equilibrium particularly at lower shear velocities. As can be seen in Figure 6-1, the present experiments were conducted under shear velocities chosen so that equilibrium could be approached within a period of time that could be recorded.

Slightly lower shear velocities for the present experiment produced the same depth of erosion as those in Chin (1985), and the progression towards equilibrium was slower. The manual operation of the adjustable sediment table raises the potential for differences in these values, as the bed is raised in response to depth of erosion as detected by eye.

Figure 6-1 Development of depth of erosion with time for A0G1 experiments with varying shear velocities, compared with data from Chin (1985)
6.2. Sediment Grading of Armoured Surfaces

The surface grading technique discussed in Section 4.3 was undertaken for all experiments from this study. While it was possible to determine the surface grading at 1.5 second increments for the duration of each study, this was not deemed necessary as the surface composition change is a relatively slow process, particularly after the first few minutes. Therefore, only the surface grading of images from the 5th, 60th and 240th minutes, as well as the initial bed, were determined. Figure 6-2 shows an example of the test section with partition by colour at each time step for experiment A0G1Q72. The $D_{50}$ and $D_{90}$ of each experiment, as determined by using this method, are provided in Table 6-1. The change in surface grading composition over time for each experiment is included in Appendix III.
Figure 6-2 Surface grading process for experiment A0GIQ72 showing the division of the surface between different sizes at t = 0 min, t = 5 min, t = 60 min and t = 240 min.
6.2.1. Critical Armour

The work of Chin (1985) enables the prediction of the maximum average grain size of the armoured bed and the maximum shear velocity at which an armour layer can form. The change in the grading curve shape over time for experiments A0G1Q60, A0G1Q66, A0G1Q72, A0G2Q66 and A0G3Q66 is shown in Figure 6-3, with the estimated maximum median grain size denoted by a cross (+), where this grain size was calculated using Equation 18 (Chin 1985). The subsurface grading curve, taken by sieve analysis prior to experimentation, is represented by the ‘Subsurface’ curve, whereas the grading curves taken throughout the experiment are the surface grading curves. Significant differences can be seen between the subsurface and surface grading curves, the origin of which stems from the difference in sample volume between the subsurface and surface grains and was discussed further in Section 4.3.4.

As can be seen in Figure 6-3, the calculated $D_{50\text{max}}$ closely matches the experimental $D_{50}$ at $t_{\text{max}}$ for every experiment. Considering that the duration of experiments conducted by Chin (1985) to determine Equation 18, was up to 5 times the duration of the present experiments, a slightly higher calculated value of $D_{50\text{max}}$ should be expected. This is the case for the $G1$ experiments, but those with a more bimodal sediment distribution ($G2, G3$) approached the calculated $D_{50\text{max}}$ relatively quickly, as the majority of the fines were entrained, leaving predominantly coarse grains to form the armour layer.

Substituting $D_{50\text{max}}$ into Shields’ equation 2.1.2 enables calculation of the critical armour shear velocity ($u^{*}_{ca}$) (Chin 1985) by using the following equation

$$u^{*}_{ca} = (\theta_{ca}(S - 1)gD_{50\text{max}})^{0.5}$$

(27)

Where if the bed is subject to stresses exceeding this value, the armour will disintegrate and the bed will erode. Use of this equation for the present study gives a value of $u^{*}_{ca} = 8.8$ cm/s at which the armour is expected to disintegrate. Experiments were generally run at shear velocities approaching this value, with observations of the sediment condition indicating shear velocities higher than $u^{*} = 8.8$ cm/s would produce an unstable armour layer. The similarity of the experimental $D_{50\text{max}}$ to the predicted value also verifies this equation, as a different $D_{50\text{max}}$ would change the predicted $u^{*}_{ca}$. 


6.2.2. Armour Layer Evolution

The change in surface grading over time is shown for the $A0G1Q66$ experiment (Figure 6-4a), and also a reproduction of the equilibrium grading curves for experiments run at $u^* = 7.4, 8.5, 9.2$ and $9.6$ cm/s from Chin (1985) (Figure 6-4b). Figure 6-4a shows a smooth
transition in shape from the initial bed to the armoured surface, where the curve rotates around the $D_{max}$ toward the $D_{50max}$. The most dramatic adjustment in topography occurs in the early stages of the experiment. In this case, a noticeable change in grading took place within the first 5 minutes of the experiment and the majority of armouring occurred within the first hour, leaving only a slight change in surface composition in the final few hours of the experiment. This compares favourably with other studies which have found that during armouring, the surface coarsens over a relatively short period of time (Chin 1985; Garde et al. 2006; Marion et al. 2003; Sieben 1999). Variation between the grading curve shape at points in time show similarity with the equilibrium grading curves at different shear velocities (Chin 1985).

![Figure 6-4 Comparison of grading curves, a) Evolution of surface grading with time experiment A0G1Q72, b) Reproduction of the equilibrium surface grading of Run 4 - Chin (1985) when run at $u^*$ = 7.4, 8.5, 9.2, and 9.6 cm/s](image)

### 6.2.3. Evaluation of Image Analysis as a Sediment Grading Tool

Grading curves of the equilibrium armour are shown in Figure 6-5, with comparison between the present study with Chin (1985) at different shear velocities. The shape of the curve is similar between studies, despite the low number of data points collected in the present study (where the availability of 5 grain sizes were measured in the present experiments, compared with percentage of the bed passing 10 sieve sizes that was used in the physical sample). An advantage of the image analysis technique can be seen by the smooth curve generated, whereas the physical sample grading curve is disjointed, probably from technical issues with the sampling or sieving.

The difference between curves at different shear velocities is much smaller for the digital analysis. This may be due to an underestimation of the proportion of fines. The digital
analysis also detected negligible change in fines over time. While a number of fines are clearly removed within the first few minutes, the lack of detection of this can be explained by observing that as the surface coarsens, the rough surface casts more shadows in surrounding depressions. It can be difficult to digitally distinguish between shadow and the grey coloured fines, therefore potentially providing a falsely high level of fines, and indicating that the digital method for surface sediment grading is unreliable at quantifying fines. Figure 6-2 illustrates this difficulty in differentiating between the colour of the grey particles, and that of shadow.

Figure 6-5 Equilibrium grading curve of the A0G166 and A0G172 experiments at $u^*$=7.5 cm/s and $u^*$ = 8 cm/s compared with equilibrium surface grading curves with $u^*$ = 7.4 and $u^*$ = 9.6 from Run 4 - Chin (1985), where the subsurface grading for all experiments was similar. Subsurface grading curve is shown by the ‘Subsurface’ curve.
6.3. 3D Surface Elevation Plots

The topography of each experiment was obtained at the start and finish of each run. A selection of the water-worked elevation plots are presented in Figure 6-6, with the initial screeded bed of A0G1Q60 for comparison (a full summary of plots for all applicable experiments is included in Appendix VII). These elevations allow the interpretation of some alternative methods of evaluating the complexity of the armoured surface, and were used to generate the PDFs of the grain size distribution, and structure functions. The elevations were detrended by using a surface determined by least squares, then eliminating any biquadratic trends. This removes any overall slope as well as larger undulations, making an unbiased surface from which to measure grain roughness (Goring et al. 1999).

![Figure 6-6 Surface elevations of experiments, a) Start of A0G1Q60, b) A0G1Q72 finish, c) A1G1Q72 finish, d) MA4G1Q72 finish, e) A0G3Q66 finish, f) A1G4Q72 finish](image-url)
Chapter 6. Armouring

6.3.1. Probability Density Properties of the Bed

The PDF for the initial and water-worked (final) bed of each experiment is plotted and grouped with other related experiments in Figure 6-7. The statistical properties for each PDF are contained in Table 6-1. Typically, an initial screeded bed will produce a tall, narrow, symmetrical PDF, indicating that the deviation of all surface elevations from the mean bed level is small. As the bed is water worked, the grains reorganise themselves, producing more varied topography. This is reflected in the PDFs of the final bed elevations; all water-worked beds display a wider and shallower PDF. The standard deviation ($\sigma_z$) of the bed relates closely to the grain size distribution, and is highly correlated to the median grain size (Aberle and Nikora 2006). Larger $\sigma_z$ indicates a broader grain size distribution. The values in this study correlate with the trend developed by Aberle and Nikora (2006), where a $\sigma_z$ of 4 mm would indicate a $D_{50}$ of approximately 12 mm, as is the case for experiment A0G1Q66.

Symmetry of the PDF is quantified by skewness ($S_k$), where positive skewness indicates that the data in the PDF is spread to the right. Previous authors have attributed positive skewness to the effects of armouring. As the bed evolves from the mean level, larger particles become more numerous on the bed surface, and fines fill any surrounding depressions, reducing the magnitude of surface elevations below the mean bed level (Aberle and Nikora 2006; Nikora et al. 1998). As expected, the plain bed experiments show an increase in skewness with armouring. The method of placing a large anchor stone in the centre of some of these experiments has a dramatic influence on the skewness, unsurprisingly, as the stone protrudes significantly; the initial skewness of these surfaces is extremely large. While still unusually high, the final bed elevations adapt to the placement of these stones and $S_k$ reduces accordingly; embedment of the stone and changes in the surface structure of the bed reduces the protrusion of the stone. Consequently, while still high, the maximum variation from the mean bed level is less than that of the initial bed. The kurtosis ($K_u$) of the distribution measures the degree of outliers in a sample. A normal distribution has a $K_u$ of 3, and the final distributions show that the plain bed experiments have values similar to this value, whereas beds with anchor stones have higher values.

The PDF shapes between experiments conducted at 66 and 72 l/s generally shows relatively little change with flow rate (with the exception of the A4G1 experiments), however, the PDF shape differs significantly when observing flows lower than 66 l/s. This aligns well with the visual observations of the experiments, where flow rates lower than 66 l/s were generally not
high enough to produce levels of sediment transport that would allow the structure of the bed to develop fully. Flow rates $\geq 66$ l/s produced beds with more complex sediment structure, and fully developed bedforms.

Figure 6-7 PDFs of initial and final bed surface elevations, a) Plain bed ($A0$) experiments with $Q = 60$, 66 and 72 l/s, b) Large anchor stone, ($A1$) experiments with $Q = 66$ and 72 l/s, c) Flat anchor stone ($A4$) experiments with $Q = 66$ and 72 l/s, d) Bimodal sediment grading (G4) experiments with $Q = 50$, 66 and 72 l/s, e) Flow rate = 66 l/s experiments with different anchor stones, f) Flow rate = 72 l/s experiments with different anchor stones
6.3.2. Structure Functions of the Bed Elevations

Structure functions were developed to describe the spatial arrangement of grains on a bed and quantify the degree of self organisation that occurs and its impact on stability (Marion et al. 2003). Originally designed for measuring turbulence, they were effectively applied to water-worked gravel beds to describe the roughness of a bed as an alternative to the typical characteristic grain size method (Aberle and Nikora 2006; Goring et al. 1999; Nikora et al. 1998). Using 3D images of the bed topography they provide information about how particles are aligned and orientated over a range of scales (Goring et al. 1999).

The 2D second order structure function $D(l_x, l_y)$ of bed elevation ($z$) is an average squared increment: $\{z(x+\Delta x, y+\Delta y) - z(x,y)\}^2$ which assesses the change in elevation between successive points on a surface. The generalised structure function ($D_G$) can be estimated from (Nikora et al. 1998):

$$D_{Gp}(l_x, l_y) = \frac{1}{(N-n)(M-m)} \sum_{i=1}^{N-n} \sum_{j=1}^{M-m} \{z(x_i + n\delta x, y_j + m\delta y) - z(x_i, y_j)\}^p$$ (28)

Where $l_x = n\delta x$, $l_y = m\delta y$, $\delta x$ and $\delta y$ are the sample intervals, $N$ and $M$ are the total numbers of measuring points of bed elevations in directions x and y respectively and $p$ is the order of the structure function. The most frequently examined structure function is of order 2, and is examined in the present study. The most important features of the 2D structure function are the gradient, saturation value and the shape of the contour, which allow interpretation of the orientation and complexity of the bed surface. These aspects of the structure functions for the topography of the experiments in the present study are discussed in the following sections.

6.3.2.1. Structure Function Cross-sections

Orthogonal cross-sections of the structure functions are taken to enable analysis of the structure function gradient. Gradients of the longitudinal ($D_{GP}(l_x, l_y = 0)$) and transverse axes ($D_{GP}(l_x = 0, l_y)$) of the structure functions are compared for different experiment groups in Figure 6-8. At small spatial lags, the gradient of the structure function is approximately linear when plotted on a log-log scale. The gradient can be approximated by $D_{G2} \propto \Delta x^{2H_x}$ and is described as the scaling region, where $H$ is a scaling exponent known as the Hurst exponent. The length of the scaling region increases with armouring, and can be expected to last for $l_x < 0.5D_{50}$ (Marion et al. 2003; Nikora and Walsh 2004). Figure 6-8 shows that this is the case.
for the majority of the experiments, where the scaling region of the initial screeded bed is less than half the median grain size of the subsurface grading \(D_{50} = 4.5\) mm, and the scaling region of the water-worked beds is less than half the median gradin size of the armoured bed \(D_{50} \approx 15\) mm. This however, is not the case for the screeded bed in the final group of experiments, where the grain distribution was bimodal, and comprised predominantly sand. This may be explained by acknowledging that the sample resolution (2.4 x 2.45 mm) was larger than the \(D_{50}\), therefore making detection of the roughness difficult.

At large lags, the structure function approaches saturation, where \(D_{G2}(\infty) = 2\delta^2\). Because this trait is common amongst all structure functions, \(D_{G2}\) is commonly normalised by this value. The area between these two regions is termed the transition zone, the upper boundary of which is expected to coincide with \(D_{90}\) (Aberle and Nikora 2006; Nikora and Walsh 2004).

Hurst exponents for the x-lag of each experiment \((H_x)\) are contained in Table 6-1; the y-lag exponents are very similar and therefore not included. It is expected that \(H_x\) increases with beds armoured at higher discharges, and correspondingly, increases with coarser grain size (Aberle and Nikora 2006). The \(H_x\) value can also be used to measure bed surface complexity, where complexity decreases as \(H_x\) increases (Bergeron 1996). This is justified by considering that on a small scale, the larger, flatter grains of an armoured surface show less features than the collection of small, medium and large grains that comprise a screeded bed.

The Hurst values for the water-worked beds from the present experiments lie in a similar range (0.54 to 0.75) to that of previous studies (0.59 to 0.67) (Aberle and Nikora 2006; Butler et al. 2001b; Nikora and Walsh 2004; Nikora et al. 1998). Generally the upper limit is within the expected range, with only one surface demonstrating a much higher than expected \(H_x\), which is unexplained. A number of the initial experiments show smaller \(H_x\) than reported, however these values are for the initial surface, which is generally less widely reported. Generally, the \(H_x\) values conform to the expected behaviour described by Aberle (2006), and reinforce the statement that the values increase with armouring flow rate.

Figure 6-9 shows a comparison between the structure functions of the beds with an anchor stone present. There are obvious differences between the initial states of the bed, however, after being water-worked, the structure functions collapse to a similar curve. Initially the \(H_x\) increases from \(A0\) to \(A4\) to \(A1\). This should be expected, considering the \(A0\) stone was the
largest. Inspection of the curve shows that this trend holds true after the bed is water worked, although is reduced.

Figure 6-8 2D second order generalised structure functions for experiment groups, symbols show $l_x$, plain lines show $l_y$, horizontal dashed lines show $2\sigma^2$ for each experiment, a) Plain bed ($A0$) varying flow rate ($Q = 60, 66, 70 \text{l/s}$), b) Large anchor stone ($A1$), varying flow rate ($Q = 66, 72 \text{l/s}$), c) Constant flow rate ($Q = 66\text{l/s}$), varying grading curve ($G2, G3$), d) Grading curve $G4$, with varying flow rate ($Q = 50, 66, 72 \text{l/s}$)

Figure 6-9 2D second order generalised structure functions for the initial and armoured beds containing anchor stones, a) Initial surface, b) Armoured
6.3.2.2. Structure Function Contour Plots

The resulting contour plots from the structure functions of the \( A0G1 \) experiment group are shown in Figure 6-10 and those from the \( A1G4 \) experiment group in Figure 6-11. Typically, an isotropic bed is characterised by circular contours and a more structured bed, with particles aligned with the long axis perpendicular to the flow direction, is characterised by an elliptical contour plot (Goring et al. 1999). These two studies agree with this generalisation, where both initial bed structure function plots show contours more circular in shape. Armouring conducted at lower flow rates in both experiment sets (\( A0G160 \) and \( A1G450 \)) display contours more circular in shape than those experiments armoured at higher flow rates (\( A0G166, A0G172 \) and \( A1G466, A1G472 \)).

Both studies exhibit a tendency for the elliptical shape of the contours to align with the long axis transverse to the direction of flow, becoming increasing aligned with increasing armouring velocity. This reflects the visual observation that some particles were oriented with their long axis transverse to the direction of flow, and is consistent with observations made by Goring (1999) Butler (2001) and Nikora and Walsh (2004), but contrasting with observations made by Aberle and Nikora (2006). Beds armoured close to the critical condition have less eccentricity than those armoured at lower flow rates (Qin and Ng 2011), which explains the reduction in eccentricity for the \( A1G472 \) experiment.
Figure 6-10 2D second order generalised structure function, a) A0G160 initial, b) A0G160 final, c) A0G166 final, d) A0G172 final

Figure 6-11 2D second order generalised structure functions a) A1G450 initial, b) A1G450 final, c) A1G466 final, d) A1G472 final
6.4. Image Analysis Study of Bed stability

When observing the bed through image analysis, it is possible to obtain a measure of the degree of stability of the surface through the image subtraction process (Section 4.5.2). By manipulating the images using a reversal of the digital subtraction of sequential frames, all particle movements between frames were removed from the original image, leaving only those particles that remained stationary over time. While actually only a step in the cluster identification process, the digital evaluation of the stability of the bed is a useful tool for visualising the armouring of the bed.

Figure 6-12 shows the proportion of the bed that remains stable after a 5 minute time lapse over the duration of four experiments. This shows how much of the bed is in flux, and therefore, how much of the bed might consist of cluster formations. This measure is useful for providing an indication of the relative stability of a surface, but the absolute results are heavily dependent on the observation period. The measured stability of the surface increases steadily with time, and fluctuations in light begin to play a role in the subtraction process if the time lapse process is too long. The 5 minute time lapse provides a long enough interval to observe the general behaviour of sediment, but not so long that light fluctuations affect the result.

As expected, the first few minutes of all experiments exhibit very low surface stability, as the initial phase of armouring commences and a high proportion of the surface fines are entrained. The stability of the surface quickly increases as the experiment progresses and most experiments display a steadily increasing fraction of the bed that remains stable over the time lapse period. The lines of similar colour show similar flow rate, and lines detailed with an asterisk indicate the stability of beds that were run with an additional, large anchor stone. Generally, the higher flow rates show higher stability, as do the experiments with anchor stones. The stability of the bed is related to the movement of particles on the surface, which is dominated by the finer fractions of the bed. Experiments with increased armouring exhibit less fines on the surface, and therefore a higher degree of stability. Even when approaching the experiment end, only 50% or less of the bed remained stable for the 5 minute observation periods. This type of analysis detects even the smallest movement of particles, so even if entrainment is very low, rocking and shifting of particles will reduce the stability of the bed.
Figure 6.12 Percentage of bed remaining stable after 5 minute long observations
Chapter 6. Armouring

6.5. Conclusions

This chapter investigates the properties of the water-worked test section. The erosion depth was obtained by measuring the difference in level of the adjustable sediment table. These values for each experiment were compared to values for similar experiments conducted by Chin (1985). The surface sediment grading was obtained through photogrammetry at intervals throughout the experiment. These grain distributions are presented, and a comparison with the final grain size distribution is made with similar experiments conducted by Chin (1985). 3D elevation plots of the initial and water-worked bed were collected for each experiment. The statistical properties of the surface elevations are presented, and structure functions are used to characterise the grain behaviour of the armoured surface.

The depth of erosion was greater in this study for equivalent shear velocities in comparison to the depths recorded by Chin (1985). The shape of the curve is similar, indicating the approach of the experiments toward equilibrium. These results highlight the variability that the manual operation of the adjustable sediment table introduces to the experiment.

Image analysis was used to successfully obtain accurate information on the surface grain size distribution of the experiment. Grading curves could potentially be obtained unobtrusively at any point in time throughout the experiment, and showed similarity with grading curves that were obtained using a physical sample. Observation of the equilibrium armour layer grain size distributions verifies Chin (1985)’s equation for the estimation of the median grain size of the critical armour layer. The change in grain size distribution over time shows that the surface changes dramatically within the first 5 minutes, and the majority of surface changes occur within the first hour.

As a bed is water-worked, the surface elevation distribution responds by becoming positively skewed. As large particles populate the surface and fines fill interstitial spaces, the magnitude of depressions between large particles decreases. These observations are consistent with those made by Aberle and Nikora (2006). The presence of a large particle on the surface modifies this response of the bed. Initially the bed is strongly positively skewed, due to the outlier presence of the anchor stone. As the bed is water worked, the surface adapts to the presence of the anchor stone, and the protrusion of the stone reduces as it embeds, therefore reducing the skewness of the distribution of the grain size elevations of the water-worked bed.
The difference between the shape of PDFs from beds water-worked at flow rates below 66 l/s was stark in comparison to flows of 66 l/s or greater. This highlights the impact of a critical shear stress in the development of an armoured bed. At flow rates too low to generate the critical shear stress, minimal sediment transport is possible and complex bed structures are unable to form.

The structure functions of the water worked surface elevations show increasing Hurst exponents with increasing armouring velocity, which, according to Bergeron (1996), indicates the surface decreases in complexity with armouring velocity. The presence of an anchor stone on the bed surface significantly changes the initial structure function curve, however, after being water-worked, such curves collapse to one very similar curve. The elliptical shape of the structure function contours align with the long axis transverse to the direction of flow, which is consistent with observations made by Butler (2001) and Nikora and Walsh (2004), but contrasting with observations made by Aberle and Nikora (2006).

Observation of the stability of the surface of the bed as it is water worked shows that the stability of the surface quickly increases as the experiment progresses. Generally, the higher flow rates show higher surface stability, as do the experiments with an anchor stone present on the surface. The stability of the bed is related to the movement of particles on the surface, which is dominated by the finer fractions of the bed. Experiments with increased armouring exhibit less fines on the surface, and therefore a higher degree of stability.

These results show that the armoured beds in this study respond to water flow in predictable ways. The equation for $D_{50\text{max}}$ developed by Chin (1905) was verified, and the PDF and structure function analysis results showed correlation with previous research results. The addition of an anchor stone impacts the dynamics of the bed, however the bed responds in ways which are understandable.
Chapter 7. Cluster Formation and Disintegration

7.1. Introduction

In order to explore the limits of the information provided by the image analysis process, a variety of aspects of the cluster formation process are presented in this chapter. In the first part of this chapter, questions are addressed that are focused around the form of clusters. How many clusters formed? How long did the clusters last? What shapes did the clusters take? How were the clusters constituted? Aspects of the quantification of these characteristics have been conducted in a number of studies to date (Brayshaw 1984; Hendrick et al. 2010; Papanicolaou and Schuyler 2003; Reid et al. 1992; Strom and Papanicolaou 2002a; Strom et al. 2004; Strom and Papanicolaou 2008). The present study differs from previous investigations either through the experimental setup, where idealised glass beads have been monitored using image analysis, or in relation to the sampling method, where manual surveys of cluster position in natural river bed situations have been conducted. The use of natural sediment and frequent high resolution imaging of the test section provides an unusual insight into the development of natural clusters in a laboratory situation.

This chapter first presents a visual description of the cluster formation process, as observed during the physical experiments, and then presents a quantification of this process by conducting an in-depth digital analysis on an individual cluster (Section 7.2). Using a survey of all experiments, the cluster type, availability, duration, composition and size are presented in Section 7.3. Cluster spacing is examined in Section 7.4, and the relationship between cluster formation, sediment transport and experimental conditions are investigated in Section 7.5. After discussing the physical attributes of the clusters that form, the second half of this chapter addresses the sediment processes that created the clusters, and the extent of their effect on the surrounding bed (Section 7.6). In these sections, the digital particle tracking (DPT) discussed in Chapter 5 is used in conjunction with the cluster identification analysis techniques discussed in Chapter 4 and results from the earlier part of this chapter. Finally, the effect of a bimodal gain-size distribution is addressed in Section 7.7. The limitations of the image analysis tools used in this study are outlined in Section 4.8 and are relevant to this chapter.
Chapter 7. Cluster Formation and Disintegration

A complete summary of the sediment transport record and cluster identification record is contained in pictorial format in Appendix V and Appendix VI, with a case study of the DPT and cluster identification process in action included as a video in digital format in Appendix VIII-D.
7.2. Observations on Cluster Development

7.2.1. Visual Observations on Cluster Development

The test section was manually mixed and flattened before each test to produce similar starting conditions. The process of increasing the flow rate caused increased levels of sediment to be entrained until the maximum flow was reached and the bed had stabilised. This initial transport was not measured because no clear picture could be taken while the water surface was fluctuating.

The first hour of experiments was characterised by high transport rates. The finer fraction of sediment reduced quickly during this period, and dune like formations were observed only during the early stages of the G2, G3 and G4 experiments, which had higher proportions of sand. The initially flat bed roughened as smaller interstitial particles were entrained, usually in bursts that varied with flow intensity. The bed surface coarsened considerably during this initial stage. The orientation of the gravel aligned quickly with the a-axis of particles normal to the flow. Particles tended to embed and rotate around their a-axis so that the c-axis lay at an angle to the bed. Of the coarser particles, the more unstable were entrained, usually rolling or sliding into more stable positions. The largest tended to embed and shift slightly, rarely moving again. Generally the larger particles that were exposed collected fines in their wake. Many of the medium sized particles rolled or saltated downstream, some settling into more stable positions against the coarsest particles to form clusters. Groups of large particles also tended to shift into more stable configurations, creating heap clusters. The presence of clusters resulted in variable topography, where raised areas containing stable clusters existed with surrounding depressions where channels of less stable particles were entrained.

Typically the cluster formation process would start with a large particle coming to rest on the bed. Within the first 30 minutes, the large particle would embed slightly, with some scour upstream, and a wake of finer particles would form in the recirculation zone behind the cluster. The size of the wake would be dependent on the size of the recirculation zone and therefore the size of the obstacle. Once established, the size of the wake would usually diminish over the duration of the experiment due to the lack of available fines in the static armour condition, preventing the replacement of any fines that were lost. Given that the flow intensity was high enough to generate the transport of particles, a stoss might form upstream of the anchor stone. Prediction of where and when clusters would form was difficult. The
erratic nature of the sediment transport of gravel means that the formation of clusters was reliant on the serendipitous entrainment of a particle upstream of the anchor stone. Additionally, this would only contribute to the formation of a cluster if that particle actually came to rest against the anchor stone, which was subject to chance. Generally, the stability of a stoss particle was dependent on the surrounding surface formation.

In a number of experiments, the addition of a significantly coarser stone to act as an initiator of clusters was tested. The anchor stone always affected the dynamic of the bed, and often became the anchor stone of a robust cluster; however this was not always the case. The significant size difference of the stone usually induced scour in front of the stone and often another area of scour was created further downstream of the stone past the wake. In all experiments, a wake formed behind the anchor stone for at least part of the time, usually at the early stages of the experiment. As with cluster formation on the rest of the bed, stoss formation was a relatively random process so would take variable times to form or not form at all. Figure 7-1 shows image sequences from two different experiments as an example of how the anchor stone responds to the flow. Figure 7-1a shows the large anchor stone, stone A1. At \( t = 0 \), the stone rests on the screeded surface before the experiment commences. The second image shows that after a very short time (6 minutes) the stone has embedded slightly and a substantial wake has formed, comprising of mostly yellow particles. At 20 minutes, the stone has embedded further and rotated around its a-axis. The wake is still present, however it is much diminished, and a stoss region of white and blue particles has formed. Figure 7-1b shows the large flat anchor stone, A4. Once again, at \( t = 0 \) the stone rests as it was initially placed on the bed. After 6 minutes the stone has rotated significantly around its a-axis, and a substantial wake has formed. 120 minutes into the experiment, the angle of repose of the stone has decreased again in response to the lack of support as the wake diminishes. At this time, a large stoss of mainly white stones has formed, completing the formation of the cluster.
Figure 7.1 Observations of cluster evolution, a) (LHS) experiment run A1GIQ72, b) (RHS) experiment run A4GIQ72. The early evolution of the wake is depicted at $t = 2$ min for both experiments (highlighted in red), with stoss formation taking a longer time to develop, $t = 10$ min and $t = 30$ min for a) and b) respectively, highlighted in red.
Chapter 7. Cluster Formation and Disintegration

7.2.2. In-depth Observation of an Individual Cluster

The cluster initiated by the addition of an anchor stone in experiment A4G171 was an excellent example of a robust cluster with clearly defined boundaries of the stoss and wake (Figure 7-1b). The life cycle of this cluster was followed using the Boundary Identification Tool described in Section 4.5.

The anchor stone was larger than the remainder of the bed. It was placed on top of the flattened bed and, as a result, the protrusion of the anchor stone at the start of the experiment enabled it to be transported a small distance, and it was repositioned at an angle (Figure 7-2). Cluster formation will only occur with exposed particles; without protrusion from the bed, the anchor stone will not influence the surrounding flow field, therefore not initiating the cluster formation process. The angle of the anchor stone in its new position provided a sheltered area behind the anchor stone where smaller particles deposited, forming the wake. The angle also reduced the disturbance to the flow that the stone created, potentially providing an area upstream of the stone with high enough shear stresses to transport stones into the stoss, but with low enough stresses that the stones were able to remain in-situ once deposited. Subsequent to the initial change in position, little movement was displayed by the anchor stone for the remainder of the experiment.

7.2.2.1. Cluster Boundary Identification

Subsequent to the initial movement of the anchor stone, the spatial boundaries of the cluster were mapped. The stoss and wake regions were outlined and superimposed over the corresponding image of the bed. Immediately after the anchor stone was deposited, a large wake region formed (Figure 7-3a). It then quickly diminished (Figure 7-3b) and fluctuated around this size for the remainder of the experiment. The size of the wake was much less dependent on the surrounding bed than the size of the stoss; it was more likely to form as a direct response to the low pressure zone created behind the anchor stone. It was large at the beginning of the experiment, but as time passed, fluctuations in the flow entrained particles at rest which were less readily replaced. Figure 7-3b shows the first particles joining the anchor stone to create the cluster, Figure 7-3c shows the cluster with the stoss fully formed, and Figure 7-3d shows the cluster immediately after the stoss disintegrated. This information was gathered for every 10th frame for the duration of the experiment, allowing quantification of the cluster size over time at 15 second intervals.
Figure 7-4 shows the size of the stoss (Figure 7-4a) and wake (Figure 7-4b) relative to the size of the anchor stone (which stays constant). Figure 7-4a shows a very clear period where the stoss is well formed between minutes 113 and 240. While it was fully formed, the size of the stoss was similar to the size of the anchor stone, with a sharp peak at the initiation of the cluster and a gradual decrease in size. Prior to the complete stoss formation there was a gradual increase in stoss size and subsequent to cluster disintegration the stoss area dropped to zero but began to increase again, possibly forming the beginning of a new cluster. In Figure 7-4b, the formation of the wake is less well defined, showing significant fluctuation throughout the experiment. Corresponding with the time at which the anchor stone was deposited to its new position, the initial size of the wake quickly grew to twice the size of the anchor stone. The wake then reduced and fluctuated significantly. During the period where the stoss was formed, the wake showed an increase in size. This occurred between minute 124 and 170. The size of the wake rose from around 0.25 to nearly 0.75 times the anchor stone size, with peaks reaching 1.5 and 2 times the anchor stone size. At its maximum, the overall size of the cluster was 4.5 times the anchor stone size, which is approximately 2% of the total test section area.

The orientation of the cluster (Figure 7-5) was determined as the angle between the streamwise direction and the long axis of the ellipse that encloses the cluster. As can be seen in Figure 7-5a, the angle of orientation of the cluster is meaningless before the cluster is formed. Once formed, it can be seen that from minute 125, the orientation becomes more constant. While still fluctuating, the orientation is generally close to 0°. The fluctuations in orientation during this period are due to the sensitivity of the cluster boundary tool, where light fluctuations and nearby white particles acting to bridge the detected area into other areas temporarily increase the detected area. The angle of orientation during the period when the cluster is well formed is shown in Figure 7-5b. This shows that while the cluster is fully formed, the majority of the time the orientation is within 6° of the streamwise direction.

The formation and disintegration of the cluster occurred despite the flow rate remaining constant for the duration of the experiment. A number of studies have predicted cluster formation cycles to follow the form of the cluster growing with increasing shear stresses, and disintegrating once the shear stress becomes too great (Papanicolaou and Schuyler 2003; Papanicolaou et al. 2003; Strom et al. 2004). Other studies have reported that clusters form on the waning arm of a flood (Brayshaw 1984; De Jong 1991; Hassan and Reid 1990).
study shows that a cluster microform can form, remain stable and then disintegrate at the same average flow rate.

The general formation process of the cluster followed a similar regime to that observed by Brayshaw (1984); the wake was the first part of the cluster to form, and stoss deposition occurred only after a relatively long period of time had passed. The deposition of one or two stoss particles appeared to assist the deposition of more particles. A large wake was observed to form immediately after anchor stone deposition, then diminish, and become larger only once the stoss formed. This has not been reported in other cluster observations, but can be explained. Wake particles have been found to have a higher transport rate than stoss particles which has been attributed to bursts in the vortex behind the anchor stone (Billi 1988; Wittenberg and Newson 2005). This may lead to entrainment of particles which settled in the wake, diminishing them over time. The addition of stoss stones to the anchor would increase the size of the obstacle, in turn increasing the size of the low pressure zone which allows wake particles to settle, and growing the size of the wake while the cluster is fully formed.
Chapter 7. Cluster Formation and Disintegration

Figure 7-2 Anchor stone positioning over the first 5 minutes

Figure 7-3 Life cycle of the cluster, a) Wake formation, b) Early stoss formation, c) Stoss formation, d) Stoss disintegration
Chapter 7. Cluster Formation and Disintegration

7.2.2.2. The Dynamics of Cluster Formation

Particles with a significant involvement in the cluster forming process were identified through observation. Each particle was then individually tracked to determine its position and orientation throughout the experiment. Using the times at which the stoss was fully formed, (Figure 7-4a), the cluster process was divided into three sections; formation, duration and disintegration. The particle movements during these three phases are presented in Figure 7-6a and b, Figure 7-6c and Figure 7-6d, respectively. The process of formation was relatively long and was influenced by two significant events. The first event was the addition of a single particle to the side of the anchor stone (Figure 7-6a). The particle gradually shifted toward the anchor stone in a transverse sliding motion, which occurred over a period of approximately one hour as is shown on the timeline. Once this first particle came to rest against the anchor stone, the cluster became a barrier for entrained particles, increasing the likelihood of deposition into the stoss region. The second important event was the disintegration of another
cluster directly upstream of the subject cluster. This occurred suddenly at minute 113 of the experiment, and followed a prior period of approximately 20 minutes, where other individual particles sporadically joined the stoss region. The disintegration of the cluster released a number of particles, three of which settled in the heart of the stoss zone, completing the formation of the robust cluster (Figure 7-6b). The particle movements relevant to the cluster, subsequent to the stoss formation, and prior to break up, are plotted in Figure 7-6c. This ‘duration phase’ of the cluster shows that movement in the stoss region is relatively frequent. The cluster is stable, however particles move both into and out of the cluster during this period. After around 90 minutes of stability, particles begin to move away from the cluster, as shown in Figure 7-6d.

Once formed, the cluster displayed a significant degree of flux. What appeared to be a stable cluster was in fact relatively active for the majority of the duration. This is consistent with observations of the entrainment and replacement of stoss particles in a stream survey made by Billi (1988). He therefore concluded that the cluster did not act as a deterrent to sediment transport. Strom et al. (2004) suggested that the cluster life cycle be broken into three phases; sediment sink, neutral and sediment source. The phase in this experiment where the cluster is fully formed compares with the neutral phase of the cluster, where particles both enter and leave the cluster. Strom (2004) referred to this also as a ‘transition’ phase, between the cluster forming and disintegrating; however in this experiment, this phase was stable for a significant amount of time. It appears that despite sediment flux occurring in the duration phase of the cluster, the cluster remained stable and was still acting as a sediment trap for generalised bed motion.
7.2.2.3. The Dynamics of Cluster Disintegration

The movements of key particles involved in the disintegration of the cluster are displayed in Figure 7-7, where all of the particles near the anchor stone were tracked over 2 minutes either side of the time of disintegration. After a long period of inactivity (Figure 7-7a), the entrainment of a smaller particle to the side of the stoss (Figure 7-7b) was a precursor to the complete breakup of the stoss, which happened less than thirty seconds later, and included the entrainment of a nearby heap cluster to the side of the stoss (Figure 7-7c, Figure 7-7d). The small particle to the side of the stoss was entrained suddenly and with little disturbance to surrounding particles after having remained stationary for 15 minutes. Shortly after the entrainment of that first particle, a large stone directly upstream of the anchor, playing a primary role in the composition of the stoss, shifted slightly, and then 1 second later was entrained along with four other particles to the side of the cluster (Figure 7-7c). In the following few minutes, other particles in the cluster shifted away from their resident

Figure 7-6 Formation of cluster, a) Initial particle movement involved in the formation of the stoss, b) All remaining particle movements involved in the formation of the stoss, c) Particle movements during period when cluster was fully formed, d) Cluster disintegration

Figure 7-7 The Dynamics of Cluster Disintegration
positions, completing the disintegration of the cluster (Figure 7-7d). The anchor stone however, remained in place, remaining available for cluster reformation.

7.2.2.4. The Effect of the Cluster on Sediment Transport

The sediment transport of larger size fractions of the surrounding bed was monitored over the duration of the experiment. This was then separated into the three primary stages in the cluster process. Also, the first 35 minutes of the experiment was separated in order to isolate the effects of armouring. Figure 7-8 shows the transport rate across the bed for the four stages; a) armouring (1-35 minutes), b) prior to cluster formation (35 – 110 minutes), c) cluster duration (110 -250 minutes), and d) subsequent to cluster breakup. The total average areal sediment transport rate for the bed in stage a) was 4.74 g/m$^2$s, in stage b) was 2.91 g/m$^2$s, in stage c) was 3.37 g/m$^2$s, and in stage d) was 2.17 g/m$^2$s. The spatial distribution of this sediment transport is depicted in Figure 7-8.
The armouring phase shows a distinct area of no sediment movement directly behind the stoss. This corresponds to the wake, which is formed in this area, resulting in only finer particles moving in this zone. Transport rates quickly diminish after the first 35 minutes, and Figure 7-8b shows only two regions of transport, one directly upstream of the cluster and the other downstream of the cluster. Figure 7-8c implies that during the period where the cluster is fully formed, peak transport rates are lower than when the cluster is non-existent. There is a particularly noticeable reduction in transport rates downstream of the cluster, with peak localised transport rates dropping from 0.12 g/m²s during cluster formation, to 0.08 g/m²s while the cluster is fully formed. After cluster disintegration, peak localised transport rates increase again to up to 0.15 g/m²s in localised areas and the zone of high transport downstream of the cluster increases in activity once again.
Figure 7-8 Sediment transport rate (particles per minute) over test section with anchor stone position drawn, a) Armouring phase (0-35 minutes), b) Prior to cluster formation (35-110 min), c) Cluster fully formed (110-250 min), d) Subsequent to cluster disintegration (250-284 min)
7.3. Physical Attributes of Clusters (size, duration)

7.3.1. Cluster Type

In addition to typical cluster formations, the existence of different types of cluster formation, in particular, line and heap clusters have been noticed in a number of studies (De Jong 1995; Strom 2006; Wittenberg 2002; Wittenberg and Newson 2005). A visual survey of 6 experiments, conducted at three times within the experiments (50 minutes, 150 minutes and 250 minutes) was taken to identify the occurrence of cluster types that formed (Figure 7-9). At all points in time, the anchor and heap clusters are the most common, line clusters generally occurred less frequently, and ring clusters seldom occurred. The survey results show evidence of correlation with the survey of two natural stream beds conducted by Strom (2008). Over time, typical clusters become increasingly predominant relative to the heap clusters.

![Figure 7-9 Cluster types]

7.3.2. General Characteristics of Cluster Formation

7.3.2.1. Typical Cluster Formation

Observing the largest stones on the bed, it was possible to digitally identify any typical clusters that formed. This was done by identifying all the red particles, and observing the bed upstream of the potential anchor stone for a distance of approximately 1 particle diameter (20 mm). By monitoring the upstream space for 10 minutes duration, the stability of the
surrounding bed was quantified. A threshold value of 50% stability was used, where any anchor stone with an upstream area that was greater than 50% stable was deemed a potential typical cluster.

A survey of all the experiments that were conducted was compiled, allowing observation of all typical clusters that formed. The sum of these at each time step is compared with the total available anchor stones present on the test section surface in Figure 7-10. This shows that only a relatively small percentage of anchor stones form clusters (Figure 7-11), and the total number of clusters that form increases over the first 120 minutes, after which time the number of clusters remains stable.

7.3.2.2. General Cluster Formation

As the bed is water worked, coherent structures begin to appear. While some of these are clusters in the typical sense of the word, others were also groups of particles similar to the other cluster types identified by Strom (2008). All of these types of clusters were grouped together, and identified by using the cluster identification algorithm discussed in Section 4.5. The development of these clusters for two similar experimental runs is presented in Figure 7-12. Additionally, the proportion of the bed that remained stable after 5 minutes of monitoring is plotted.

The surface area covered by typical clusters lies close to 2% for the majority of the time in both experiments. This is dwarfed by the proportion of other clusters, which rises to around 20% in both experiments. In comparison to the survey in Section 7.3.1, typical clusters are under represented in the quantification of the surface coverage. This is because the typical
cluster detection tool only included those that contained a red anchor stone, leaving out any that may have formed with only white particles. Additionally, the values in Section 7.3.1 are from a tally, whereas the surface coverage works with area, where the heap clusters and other types such as ring, are often much larger and have a greater rate of growth than the typical anchor stones.

The boundary between where a clustered surface turns into a fully armoured surface is unclear, however the surface coverage of both experiments appears to flatten as 20% of the surface is covered with stable clusters, potentially indicating that at this point, no additional clusters will form and the surface is fully armoured. Knowledge of the armoured surface obtained from Section 6.1 confirms this observation interpretation.

In experiment A1G1Q66 (Figure 7-12a), the cluster formation is steadily progressive over time, slowing as it approaches the maximum coverage for the bed. However, in experiment A1G1Q72 (Figure 7-12b), the proportion of clustering on the surface approaches this limiting value relatively early in the experiment, only to quickly drop back to a lower value, after which point the proportion of clustering on the surface steadily grows again, until 20% coverage is reached later in the experiment. This indicates that there is a limit to the proportion of clusters that are able to be formed on the bed that is dependent on the sediment transport or degree of armouring of the bed.

Following this idea, Figure 7-13 and Figure 7-14 show the relationship between the maximum surface coverage of the clustered bed and the shear velocity for each experiment. Figure 7-13 shows relatively small variation with shear velocity. The maximum surface coverage...
coverage of clusters is generally less than 5%, and is less than 1% in some cases, with only a couple of experiments reaching 6% maximum surface coverage. Ultimately, in this case, the number of typical clusters that form is limited by the availability of anchor stones on the bed surface. Figure 7-14 shows significant scatter amongst the runs, with surface coverage ranging between 5 and 34%. At the highest shear velocities, the percentage coverage approaches the theoretical maximum surface coverage of 40% that was suggested by Wittenberg et al. (2007). The effect of placing the anchor stone on the surface is apparent, with the majority of plain bed experiments displaying a smaller proportion of clustered surface than those beds with anchor stones placed. This suggests that with the addition of an artificially placed large stone, clustering may be encouraged, likely improving the stability of the bed.

7.3.3. Cluster Duration

By observing the lifespan of all of the clusters that were detected, the duration of cluster existence was recorded. This concept is complicated slightly by the arbitrary ending of the experiment, where some clusters which might have otherwise disintegrated, were not allowed to evolve to completion. Figure 7-15 shows a graphical representation of the period of time over which the detected clusters existed for experiment A1G1Q66. Each horizontal line represents one cluster. The time at which it was detected is represented by the start of the line and the point at which it disintegrated is represented by the termination of the line. A vertical line at any point along the abscissa shows how many clusters were in existence at that time. For example the red line drawn at t = 60 minutes in Figure 7-15 shows that at that time, 14
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cluster are present on the bed. Inspection of the final minute of the experiment shows that a number of clusters were fully formed.

For analysis of the cluster formation duration, all experiments were grouped together. Of 875 clusters identified in 11 runs, 30% of clusters remained intact for the remainder of the experiment once they had formed. In these experiments, by definition, a group of particles was only labelled as a cluster if it remained intact for longer than 60 minutes. Figure 7-16 and Figure 7-17 show that clusters that form are more likely to remain intact for over 120 minutes. The clusters that did not remain intact for the remainder of the experiment existed most frequently for 120 minutes, with a decrease in frequency as time increased.
7.3.4. Cluster Size

The size of a cluster is difficult to define considering the constant state of flux of the bed. The formation size of the cluster can differ from the size of the cluster during its evolution. The change in cluster size and shape over time has been investigated in an attempt to define a ‘characteristic size’ of the cluster. The analysis was simplified to some extent by eliminating any parts of the cluster that consist of grains smaller than the $D_{80}$. This leaves only the ‘core’ of the cluster for analysis, typically the stoss and the anchor regions, although these definitions vary slightly for clusters of other form, e.g. heap, ring, etc. Figure 7-18a and Figure 7-18b show the average size and major axis length of all detected clusters. Few clusters have an average size less than that of the $D_{98}$ particles the majority of the clusters have a size similar to twice the $D_{98}$ particle, and the maximum cluster size reached 11 times the $D_{98}$ particle area. All clusters had a major axis length greater than that of the $D_{98}$, and the majority of particles ranged in size between 2 and 4 times the $D_{98}$ axis length.

Because cluster size is variable as time progresses, the variation in individual cluster size during the existence of the cluster was measured. The minimum cluster area was subtracted from the maximum cluster area, and normalised by the $D_{98}$ area. Figure 7-18c shows that while most variation was small, many clusters changed size substantially. Comparison between the initial cluster size and the average cluster size (Figure 7-18d), shows that generally the clusters increase in size, and the small number that decrease in size tend to remain at a similar size to that at formation (indicated by the dashed 1:1 ratio line on the graph).

The size of the cluster appears to affect the duration of the clusters existence, as can be seen in Figure 7-18 e) and Figure 7-18 f). Both a larger average cluster size and a longer major axis generally result in an extended duration, as shown by the red linear regression trend line. This trend is exaggerated when observing the average cluster size and shows a significant decrease in the scatter of this relationship.
Figure 7-18 Cluster size, a) Histogram showing the variation in average cluster surface area of each cluster identified, b) Variation in the average major axis length of each cluster identified, c) Variation of the cluster size within the duration of the clusters existence, d) Relationship between the average size of each cluster and the initial size of the cluster, with dashed line showing unity, e) Relationship between the average size of each cluster and the duration for which they remained on the bed, red line showing the linear trend (using the least squares method), f) Relationship between the average major axis length of each cluster and the duration of time that it remained on the bed red line showing the linear trend (using the least squares method)
7.3.5. Cluster Composition

While the development of clusters is obviously time dependent, for the sake of simplicity, the composition of individual clusters was observed at particular times. Observing the collection of typical clusters that were formed at any instant and grouping them together, the distribution of sized particles was observed upstream and downstream of the stone. The length scale was normalised by the size of the relevant anchor stone.

Figure 7-19 shows the average grain size composition of all clusters at various times. The central red parabola represents the average anchor stone, and the other coloured lines represent the average proportion of each group of coloured stones in the strip of bed extending upstream and downstream from the anchor stone. The figures clearly show the stoss region of the clusters, which extends to 1 anchor stone diameter distance upstream of the anchor stone. At this position, there is a corresponding decrease in the green, yellow and grey stones. Further upstream of the anchor stone these features quickly disappear and a random assortment of grains dominates. Immediately downstream of the anchor stone, there is a rise in the grey particles representing the wake that is present at each time step. On average this wake extends to only about 0.5 times the length of the anchor stone. Observing the grain size distribution when normalised by the fraction of each grain size available on the surface exaggerates these trends (Figure 7-20). The availability of white particles upstream of the anchor stone rises to twice that of the remainder of the bed, and the fines in the wake approach a similar value. Also observable in this normalised figure is the appearance of exaggerated values of the white and green particles downstream of the stoss. A potential cause for this is the high shear zones on either side of the anchor stone transporting larger fractions past the stone, but reduction in stress past the stone causing the deposition of the particles slightly downstream of the stone.
Figure 7-19 Average grain size composition of all clusters along the stream wise direction at, a) $t = 30$, b) $t = 60$, c) $t = 120$, d) $t = 180$ and e) $t = 300$ minutes.
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7.3.6. Anchor Stone Properties

Investigation of the characteristics of the anchor stone that may encourage clusters to form was conducted by comparing physical attributes of anchor stones that formed clusters with those that did not. The box plots in Figure 7-21 show these comparisons. The important features for interpreting these box plots are that the red line in the middle of each box is the sample median, the top and bottom of each box is the 25th and 75th percentile of the sample, the lines extending from the box (whiskers) show the extent of the 99th percentile and the red crosses at the limits of the boxes are outliers. The notches display the variability of the medians, where notches that do not overlap have different medians at the 95% significance level.

The features of the anchor stones that were tested were the area, long axis length, ratio of long to short axis lengths and orientation (Figure 7-21). The most prominent difference between the two data sets can be seen when comparing the ratio of long and short axis of the anchor stones. This ratio represents the shape of the stone, where smaller values represent rounder stones, and higher values represent more oval shapes. This comparison indicates that more oval shaped stones are more likely to produce clusters. This finding is consistent with the observation of clusters during the experiments that the oval shaped stones more frequently formed stable clusters. When elongate particles rest with their long axis transverse to the flow, they expose a greater obstruction for any approaching particles, increasing the likelihood for particle entrapment. Additionally, the relatively short height and or width of an elongate particle pose less of an obstruction to the surrounding flow field by reducing the higher shear velocities created by the obstruction from re-entraining the particles. Brayshaw...
(1984) noted that river beds containing elongate particles form larger clusters due to an increased potential for interlocking than beds containing rounded particles. None of the other features compared showed any significant effect.

Figure 7-21 Comparison between anchor stones that formed clusters and those that did not, a) Area, b) Long axis ($l_c$), c) Ratio of long to short axis, d) Anchor stone orientation. The red line in the middle of each box is the sample median, the top and bottom of each box is the 25th and 75th percentile of the sample, the lines extending from the box (whiskers) show the extent of the 99th percentile and the red crosses at the limits of the boxes are outliers. The notches display the variability of the medians, where notches that do not overlap have different medians at the 95% significance level.
7.4. Spatial distribution

The arrangement of clusters on the bed surface is an intricate affair. As more clusters form over time, their spatial distribution must be affected by the occurrence of other nearby clusters. The increased shear stress along the sides of a cluster is thought to discourage other clusters from forming in the immediate vicinity (Wittenberg et al. 2007).

7.4.1. Average Spatial Distribution

The distribution of clusters along the test section was observed by collating the positions of all the clusters in each experiment. The spatial distribution of the clusters is shown for the stream wise (Figure 7-22) and transverse directions (Figure 7-23). Along the stream wise direction, most clusters tended to form at the upstream end of the test section, with the number of clusters decreasing gradually along the length of the section and dipping sharply toward the downstream limit. This can be explained by considering the progression of armouring along the bed. As the upstream surface is the first to armour, this is where the bed will first stabilise, therefore providing a stable environment for clusters. The higher rates of transport at the downstream end of the test section correspond to a less stable bed, and reduced cluster formation, at least until the surface has armoured. The distribution of clusters along the transverse direction shows that there are three peaks; one on either side of the bed, close to the flume wall, and a third, central peak. The added stability that the flume wall provides, coupled with the reduced velocity from the side wall effect explains the preference for clusters to reside at the side of the flume. The central peak most probably arises from the experiments that contained a central anchor stone. The added stability that the stone lends to the bed encourages cluster formation.
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7.4.2. Temporal and Spatial Distribution

Delaunay Triangulation (De Berg et al. 2008) was used to connect each cluster to its natural neighbour. The triangulation connects only the points that can be linked without entering another triangle’s circumscribed circle. Figure 7-24 and Figure 7-25 show the spatial distribution of clusters on the test section as the experiment progresses over time. A snapshot of the cluster arrangement is shown at 10 minute intervals for experiments A0G1Q66, A0G1Q72, A1G1Q66 and A1G1Q72 (Figure 7-24) and A4G1Q66, A4G1Q72, MA4G1Q66 and MA4G1Q72 (Figure 7-25) (full record is included in Appendix VI). Each cluster is connected to its natural neighbour, creating a network of triangles on the bed surface, which becomes more dense as time progresses.

These figures show that in general the formation follows a trend where cluster formation is initiated at the upstream end of the test section and progresses downstream over time. Clusters appear to form in similar areas, where, if a cluster is already present, it is more likely that other clusters will form nearby. In a number of cases (Figure 7-24b, Figure 7-24d, Figure 7-25a, Figure 7-25b) this phenomenon can be clearly seen to occur. In these experiments, the clusters are prevalent in the upstream section of the bed early in the experiment. As time progresses, one or two clusters form in the downstream section of the bed. These downstream clusters are quickly joined by others, forming a network of clusters in the downstream section of the bed as well as the upstream section, in some cases leaving a more sparse distribution in the centre of the bed (Figure 7-24b, Figure 7-25a, Figure 7-25d).

An upper limit for the degree of clustering of a bed is apparently reached in the experiments where many anchor stones are placed (Figure 7-25c, Figure 7-25d). The degree of clustering in these experiments is less than that in the majority of the other experiments. As predicted by Wittenberg (2007), this is most likely due to the high shear stresses generated on the sides of clusters, which discourages more clusters from forming. Because these anchor stones are significantly larger than the remainder of the bed, they generate higher stresses, leading to a lower upper limit for the degree of clustering for the bed.
Figure 7-24 Graphic showing cluster positions on the test section for each experiment at 10 minute intervals, where time progresses from left to right then top to bottom. The blue lines are the Delaunay Triangulation lines that join nearby clusters to one another. a) A0G1Q66 b) A0G1Q72, c) A1G1Q66, d) A1G1Q72
Figure 7-25 Graphic showing cluster positions on the test section for each experiment at 10 minute intervals, where time progresses from left to right then top to bottom. The blue lines are the Delaunay Triangulation lines that join nearby clusters to one another, a) A4G166, b) MA4G172, c) A4G166, d) MA4G172
7.4.3. Distance Between Clusters

By measuring the connecting lines of the clusters, it is possible to quantify the degree of isolation of each cluster, giving an indication of the distances between each cluster and its nearest three neighbours. The distribution of these values is presented in the form of a box plot for experiments A1G166 and A1G172 (Figure 7-26). Figure 7-27 shows the distances normalised by the major axis length of each cluster. Normalising the distances does not change the pattern significantly.

As the experiment progresses it appears that the distances between clusters become more constant. While outliers still exist, the median and upper and lower quartiles stay similar for the latter stages of the experiments. The median distance between clusters tends to shorten toward approximately the same length as the major axis length ($l_c$) of the cluster. The maximum distance between clusters was up to $5l_c$, equivalent to almost 300 mm or 1/3 of the test section. The majority of clusters remained at least $0.5l_c$ apart from neighbouring clusters, however some formed at distances less than this, with the nearest being $0.2l_c$.

![Box plots showing distribution of distances between clusters over time for experiments A1G166 and A1G172.](image)
Figure 7.27 Distribution of distances between the nearest neighbour of each cluster ($d_c$), normalised by the major axis length of the respective cluster ($l_c$), at 30 minute time steps for the duration of each experiment, a) A1G1Q66, b) A1G1Q72.
7.5. The Effect of Clustering on Sediment Transport

7.5.1. Total Average Transport Rates

The average aggregate areal sediment entrainment rate ($e_i$) was calculated for the first 300 minutes of each experiment using the methodology described in Section 4.4.5 (Figure 7-28). On the basis of the method used by Petit (1994) to calculate the entrainment threshold for the gravel bed, $u^*$, was calculated for the smallest grain size that was tracked (red dotted line). At shear velocities only slightly higher than this value, the average entrainment rate of the particles rises steeply. As expected, the entrainment of particles increases with shear velocity. After the initial rise, the entrainment of particles from the plain bed experiments appears to flatten. It is proposed that this change in gradient arises due to armouring of the bed, where the degree of armouring is similar at shear velocities between a certain range, resulting in a limited amount of entrainment from the bed and therefore similar entrainment rates. The impact of the addition of anchor stones is clearly apparent, particularly at lower shear velocities. Experiments run at similar shear velocities display higher entrainment rates than similar experiments containing a larger anchor stone on the surface. This is less apparent at higher velocities.

This trend indicates that the presence of one or more stable particles on the bed strongly influences the entrainment of other particles, at least within certain flow conditions. This aspect is investigated further in the following sections by exploring particle cluster interactions.

![Figure 7-28 Average areal aggregate sediment entrainment rate for each experiment duration (t = 0 to 300 min), with respect to the experimental shear velocity. The presence and type of anchor stone is indicated by marker type, and the red line indicates the theoretical entrainment threshold for D = 9.5 mm](image-url)
7.5.2. Spatial Distribution of Sediment Transport Record

Figure 7-29 and Figure 7-30 show a summary of the sediment transport and cluster behaviour of experiments A0G172 and A1G172 respectively. Particle movements, shown as pathlines for individual particles, avoid the additional larger stones when they are present on the bed and in some cases appear to follow common pathways (Figure 7-29a Figure 7-30a). Inspection of the position of the areal totals of particle movements aggregated over incremental areas on the beds shows a tendency for the highest sediment transport rates to be concentrated in the downstream section of the test bed (Figure 7-29b and Figure 7-30b). Sediment entrainment is not evenly distributed across the bed, and is concentrated in specific areas. A compilation of all particle track records is given in Appendix V.

Comparison of the areal aggregate sediment entrainment rate \(e_i\) over time, with the degree of surface clustering indicates there is a relationship between these two phenomena (Figure 7-29c and Figure 7-30c). The height of the adjustable sediment table is included in the time series for completeness, as the role that the change in bed level plays in promoting sediment transport is unclear, and therefore should not be ignored. The red dotted lines on each figure indicate either a peak or trough in the degree of clustering on the bed. Particularly apparent in Figure 7-30c, is a dip in the entrainment rate when surface clustering is high and an increase in entrainment when the proportion of surface clustering decreases. A full record of the relationship between \(e_i\), the proportion of clustering and the depth of erosion for each experiment is included in Appendix IV.

Because the sediment transport rate is inherently decreasing as the experiment progresses, and the stability of the bed is correspondingly increasing, it is difficult to separate the influence of clusters on the transport rate. However the interactions between sediment transport and the degree of clustering on the surface in these figures indicates that the cluster plays a role in attenuating sediment transport.

This relationship is explored further in Figure 7-31 and Figure 7-32, for experiments A0G172 and A1G172 respectively. Each image in these sequences shows a 50 minute long time lapse of the bed, with the positions of clusters that are stable over this time depicted as red circles, and the surrounding particle track record for the time lapse duration shown as pathlines (with pathline colour indicating the time of movement according to the same colour bar as Figure 7-29a). In many instances the position of the pathlines indicates that the moving particles avoid most of the clusters. Foremost, these results show the dynamic nature of clusters. While
they are significantly more stable than the remainder of the bed, over an extended period of time they are inclined to fluctuate.

While clusters (in this case) are, by definition, areas with a high density of particles that remain stable for extended durations, and therefore should not contain a large amount of movement, it seems that in some cases, a high degree of clustering reduces entrainment from beyond the boundaries of the immediate cluster. In addition to this, in some cases, although clustering is present, it is difficult to tell if this reduces the total rate of entrainment, or simply concentrates movements in areas with no clustering.
Figure 7.29 Particle track record for experiment A0G172, a) Pathline of each particle movement, with time scale indicated by colour b) Areal total entrainment rates aggregated over incremental areas, c) Percentage of surface clustered, areal transport rates ($\epsilon_i$) and adjustable sediment table level over time.

Figure 7.30 Particle track record for experiment A1G172, a) Pathline of each particle movement, with time scale indicated by colour b) Areal total entrainment rates aggregated over incremental areas, c) Percentage of surface clustered, areal transport rates ($\epsilon_i$) and adjustable sediment table level over time.
Figure 7.31 Sequence showing the position of clusters and the surrounding particle track record for consecutive 50 minute durations, A0G172. Pathline colour same as in Figure 7-29.

Figure 7.32 Sequence showing the position of clusters and the surrounding particle track record for consecutive 50 minute durations, A1G172. Pathline colour same as in Figure 7-29.
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### 7.5.3. Spatial Relation of Sediment Entrainment with Clustering

The relationship between the presence of clusters on the bed, and the entrainment of particles in that area was investigated. This follows the findings of Wittenberg et al. (2007), who proposed the concept of an optimal spacing between clusters, and a corresponding maximum surface coverage of clusters on the bed. To observe the local effect of clusters, the bed was divided into a grid. The total size of clusters in each grid section, for each time step, was recorded, as was the total sediment entrainment rate. Each grid section was inspected at each time step to determine both the percentage of sediment entrainment and of clustering that occurred relative to the overall rates. This was done for each 50 minute time step, for each experiment and repeated using different grid sizes (3x3, 4x4 and 2x2). The relationship between clustering and sediment entrainment for the different grid sizes is presented in Figure 7-33.

Figure 7-33a shows the relationship between the average entrainment rate and percentage of clusters present for the whole test section for each 50 minute period of each experiment. Overall, when the degree of cluster cover on the bed increases, the average sediment transport rate for that duration decreases slightly. This is the expected result, as over time, clustering increases and sediment transport decreases, which would create an underlying trend.

The proportion of entrained particles with respect to the presence of clusters at different grid sizes was calculated, where both the clustering and entrainment values in each grid section are normalised by the amount of clustering or entrainment for the whole bed at each time step. This was done because of the time variability of entrainment, and therefore enables the measurement of the influence of clusters on the position of entrainment independently of the degree of armour on the bed. Only grid sections that contained significant coverage of clusters (>33%) or minimal coverage of clusters (<10%) were observed. This removed the bulk of data, where there was minimal cluster coverage and random levels of particle entrainment, leaving only the cases where clustering was prominent enough to have a noticeable effect on the rate of entrainment. Figure 7-33b, Figure 7-33c and Figure 7-33d show comparison of the rate of entrainment at low and high coverage of clusters (2x2, 3x3 and 4x4 respectively). For all grid sizes there is less entrainment of particles with a high proportion of clustering. In other words, considering all the entrainment from a bed, at any point in time, on average there is likely to be slightly lower entrainment in areas with higher amounts of clustering present.
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7.6. Particles Entering, Leaving and Bypassing Clusters

This section addresses the effect of clusters on sediment transport from a slightly different perspective, that of the sediment. By knowing the time and position of all particle movements and cluster locations, the particle movements that intersected within the boundaries of all identified clusters were detected. The bed surrounding each identified cluster was examined in time steps relative to the time at which the cluster formed.

An example of the types of movements that were detected for each individual cluster from one experiment is shown in Figure 7-34 and Figure 7-35 shows each individual cluster that was formed in experiment A1G1Q72, with the cluster’s formation particle movements.
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Figure 7-34 Example of the cluster forming particle movements

Figure 7-35 Montage showing each cluster from experiment A1G1Q72 and its position on the bed, with the cluster forming particle movements showing in red
7.6.1. Cluster Formation

All particle movements for particles that landed inside the cluster region within 50 minutes prior to the first detection of the cluster were collected for each cluster in each experiment. These movements were considered to be the cluster-forming movements. Each particle track was normalised with respect to the cluster position \((x_{ci}, y_{ci})\), enabling the conglomeration of particle tracks into one representative cluster (Figure 7-36a). The direction and distance of each of these particle forming tracks is then presented in a modified rose diagram (Figure 7-36).

The majority of cluster-forming particle movements are aligned with the downstream direction, especially for those particles that came from a greater distance away. Particle movements closer to the cluster feature a much wider range of angles, indicating that the process in forming a cluster includes the attraction of nearby particles moving at angles to congregate together.

![Figure 7-36 Particle interactions with clusters, a) Particle movements approaching a clustered region in the period leading up to the detection of that cluster, b) Direction from which the particles approach the cluster, with colour bar indicating the distance from which particles approach](image)

7.6.2. Cluster Duration

The area around the cluster was monitored from the time that it was identified as a cluster to the time that it was no longer detected. Any particle movements that were detected entering to, or departing from the cluster area were collected for analysis. As with the formation movements, all of the clusters were assimilated into one data set and analysed as such. Figure 7-37 depicts the detected particle movements, where each particle track is coloured according to whether it is entering or leaving the cluster. Figure 7-38a and Figure 7-38b show the
direction and distance that the particles travel when entering and leaving the cluster respectively. In both the forming and disintegrating movements, the angle at which particles enter or leave the cluster is less than those of the cluster formation period, with over 30% of particles entering or leaving within $\pm 5^\circ$ of the stream wise direction.

Figure 7-37 Particle movements approaching the cluster region (black) and away from the cluster region (red) for the duration that the cluster is fully formed.

Figure 7-38 Direction of particle movement approaching and departing the clusters while the cluster is fully formed, with colour bar showing distance travelled by the particles (pixels), a) Cluster forming movements, b) Cluster disintegrating movements.

7.6.3. Cluster Disintegration

In the same manner as in Sections 7.6.1 and 7.6.2, the cluster region was monitored for the 50 minutes subsequent to the final time at which the cluster was fully formed. Figure 7-39a and Figure 7-39b respectively show the particle movements and directions of particles leaving the cluster. The direction and distance of particles leaving the cluster as it disintegrates are similar to those that left the cluster while it was fully formed.
Figure 7-39 Particle interactions with clusters, a) Particle movements leaving a clustered region in the period subsequent to the disintegration of that cluster, b) Direction of the particle track line as the particle moves away from the cluster, with colour bar indicating the distance that particles travel

7.6.4. Summary of Particle Interactions

The proportion of movements involved in forming a cluster was recorded for each experiment. The particle track positions were also inspected to assess whether the respective particles had the opportunity to enter a cluster. Those particles that were entrained from directly upstream from a cluster, but did not join the cluster, were deemed to bypass the cluster. The proportions of particles that did, and did not, join a cluster, as well as those that bypassed a cluster are presented in Figure 7-40, where the box plots show the distribution of these proportions between experiments. On average, only 25% of all particle movements relate to particles that joined a cluster, with generally very little deviation amongst different experiments. Approximately 35% of particle movements bypassed clusters, with a greater deviation between experiments.

Of the approximately 25% of particles that were involved in the clusters, the division between roles is shown in Figure 7-41. The percentage of particles is fairly evenly distributed between the cluster forming, entering once the cluster is formed, leaving while the cluster is formed, and leaving as the cluster disintegrates. The percentage of particles entering and leaving the cluster during the period where the cluster is fully formed is generally slightly less than those entering to form the cluster or leaving as the cluster disintegrates. Overall, the number of particles entering the cluster is similar to those leaving the cluster, as might be expected when the cluster process evolves from formation to disintegration.
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Inspection of particles that bypassed the clusters is depicted in Figure 7-42 and Figure 7-43. Comparison of the distance from which the particle approached the cluster between those that entered and those that bypassed the cluster was conducted using a histogram. The smooth shape of the bypass histogram indicates a random distribution, whereas the histogram showing the particle movements that entered the cluster is steeper, indicating that particles entering the cluster are more likely to come from a closer proximity to the cluster. This effect is likely exaggerated by the particles that come from more transverse directions, of which there are many, with these predominantly moving shorter distances to reach the cluster.

![Figure 7-40 Distribution of the percentage of particles in each experiment that form clusters, do not form clusters, and bypass a cluster from a position directly upstream of the cluster](image)

![Figure 7-41 Percentage of total particle tracks involved in clusters for each experiment, where Dur (F) and Dur (D) refer to particles that enter or leave the cluster during the period when the cluster is fully formed, respectively, and Dis refers to particles that leave the cluster as the cluster disintegrates](image)

![Figure 7-42 Particle movements approaching (black) and bypassing (red) a cluster](image)
Figure 7-43 Origin of particles, distance from cluster a) Cluster forming movements b) Bypassing movements
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7.7. Bimodal Sediment Experiments

A number of bimodal sediment experiments were conducted to investigate the effect of sediment grading on the formation of clusters. In a natural setting, bimodal sediment has been observed to induce cluster formation more readily than uniform grading (Hendrick et al. 2010). In the uniform G1 grading experiments, the formation of clusters was successful, however, studies with a large anchor stone placed on the bed have indicated that bimodal sediment might further encourage cluster formation. Three different sediment compositions (G2, G3, G4) were tested, in addition to the original grading (G1), the grading curves of which are shown in Section 3.5.4. The G4 sediment was also run at 50 l/s and 72 l/s (A1G4Q50 and A1G4Q72), allowing investigation of the effect of flow intensity.

7.7.1. Visual Observations

These experiments were observed with the aim to find a sediment composition that would form clusters more readily than the original grain size distribution. The different sediment compositions were run at the same flow rate (66 l/s), using experiments A0G1Q66, A0G2Q66, A0G3Q66, and A1G4Q66. A pictorial summary of these experiments is shown in Figure 7-44, with images from $t = 0$, $t = 5$ minutes and from the final image from each experiment. The pathlines from the particle track record of the large particles (> 9.5 mm) is also included.

Figure 7-44a shows the G1 grading, which is discussed comprehensively in previous sections. This uniform sediment grading provided a point of comparison for the bimodal sediment experiments. Figure 7-44b shows the results for the G2 grading, which was an intermediate curve, with 50% sand. The sediment used for experiment A0G3Q66, shown in Figure 7-44c, was extremely bimodal, with 80% sand, then a large gap in grain size, with the remainder of the bed comprising of coarse pebbles $D_{min} = 9.5$ mm. This experiment armoured extremely quickly, and within 30 minutes the surface was almost completely covered in the coarse particles. Finally, as shown in Figure 7-44d, a similar grading to G3 was tested, however the gap between the sand and coarse grains was filled with intermediate sized particles.

In general, observation of the experiments indicated that higher sand content enabled a greater degree of sliding motion, where particles could slide into more stable positions. Particle movements were more stochastic in the uniform bed. The lower sand fraction meant less opportunity for particles to embed, making saltating movement more common.
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Figure 7-44 Summary of various grading curve experiments, at time = 0 min, t = 20 min, and $t_{\text{max}}$ (the maximum duration of each experiment), with the pathlines of the large particle movements for each experiment, a) A0G1Q66, b) A0G2Q66, c) A0G3Q66, d) A1G4Q66.
7.7.2. Cluster Forming Properties of Bimodal Sediment Beds

The average sediment transport is shown in Figure 7-45, and time dependent entrainment is shown in Figure 7-47. The extremely high entrainment rate of G3 is due to the short experiment duration, as the experiment was characterised by high movement while the sand was entrained, and then a uniform armour layer. Experiments A0G2Q66 and A1G4Q66 have a similar average entrainment rate, however due to the decrease in transport rate over time, the short experiment duration for A1G4Q66 artificially increases this mean value. At similar shear velocity and test duration, experiment A0G1Q66 shows slightly higher entrainment than A0G2Q66. The three G4 experiments run under differing flow intensities show an exponential increase in entrainment, as the highest shear velocity was approaching the critical armour threshold for the bed (Figure 7-45, pentagram symbols).

The formation of clusters in experiment A0G3Q66 was difficult to identify, the lack of intermediate sized particles prevented the formation of a stoss or wake, or any contrast between clusters and other features. This experiment was not included in the cluster studies. The maximum surface coverage for the other grading compositions (G1, G2 and G4) is shown in Figure 7-46, and the evolution of clusters over time is shown in Figure 7-48. The surface coverage of cluster formation was within the ranges observed in the previous G1 experiments (between 5 and 34% surface coverage), however the G2 bimodal experiment was at the higher end of this range. Although stopped prematurely, experiment G4 showed a similar strong development of clustering during the first hour of the experiment. These results concur with the survey of Hendrick et al. (2011), indicating that bimodal sediments form clusters more readily than uniform sediment grading.
velocity

Figure 7-47 Variation in the sediment entrainment rate for various sediment grading over time (10 minute time average)

Figure 7-48 Variation in the percentage of surface covered by clusters for various sediment grading over time
Chapter 7. Cluster Formation and Disintegration

7.8. Conclusions

This chapter investigates the formation of clusters on the test section under different flow and sediment conditions. Firstly, a descriptive observation of the cluster mechanics is discussed and then results from the cluster identification tool are presented. Finally, DPT is combined with the cluster identification results to investigate the interactions of particles with clusters. While there are limitations to the image analysis tools due to the technically difficult nature of the study, future improvements in image analysis technique would increase the accuracy and scope of the analysis process.

Clusters were successfully formed and observed in these experiments. The addition of a large anchor stone was intended to instigate cluster formation, however this was not always successful. While most of the larger particles readily formed a wake, cluster formation was often dependent on the serendipitous deposition of a stone into the stoss of the anchor stone.

The in-depth observation of a large, robust cluster showed that a large wake readily formed, and diminished over time. Formation of the stoss was much slower, and was initiated by the movement of a large stone slowly creeping in a transverse direction toward the anchor stone. This created a barrier for sediment movement, which trapped a number of stones when an upstream cluster disintegrated and released stones. The wake of this cluster generally fluctuated between 0.25 and 0.75 times the anchor stone size, and the size of the stoss remained constant, at around the same size as the anchor stone. These values are consistent with those observed in the survey of all typical clusters, where the average stoss length was the same as the anchor stone diameter, and the wake was 0.5 times the anchor stone diameter. The disintegration of the cluster was triggered by the entrainment of a small particle from a nearby cluster. The effect of the cluster on the overall sediment entrainment of the bed appeared to reduce localised peak transport rates, particularly those downstream of the cluster.

The variation in cluster types present on the test section was similar to cluster types that have been reported in other studies. Typical and heap clusters were most common, with typical clusters becoming increasingly prominent over time. Out of all of the anchor stones thought to be available to form clusters (those coarser than the $D_{90}$), only around 22% actually formed clusters. Investigation of these clusters indicated that particle shape plays a role in cluster formation, where elongate stones form more stable clusters.
Inspection of the coverage of the test bed surface with clusters over time showed that the proportion of clusters present on the surface tends to grow with time until it reaches a maximum amount. This study indicates that there is a limit to the proportion of clustering allowable on the surface, which is dependent on the sediment transport rate or degree of armouring on the bed. The maximum surface coverage with clusters for all experiments ranged between 5 and 34%. Surface coverage increased with increasing shear velocity, and the proportion of clustering present was potentially encouraged by the presence of a large anchor stone.

In a survey of the duration of all the clusters that formed, 30% of clusters remained intact indefinitely (until the end of the experiment). Of the clusters that disintegrated, the most common duration was 120 minutes, with decreasing numbers of clusters remaining intact for duration times longer than this.

Cluster formation was generally initiated at the upstream end of the test section, and spread downstream as the experiment progressed. Over time, the distance between clusters decreased, with an average equilibrium spacing of \(0.5l_c\), and a range between \(0.2l_c\) and \(2l_c\). Clusters were more likely to form in areas where other clusters were already present. Overall, the spatial distribution of clusters was concentrated at the upstream end of the test section, and in the transverse direction, towards the sides of the flume.

The total average areal entrainment rates \((e_i)\) were significantly decreased in experiments where an anchor stone was placed on the surface. This trend was most apparent at low shear velocities. Comparison of the sediment track record with the proportion of surface clustering over time indicated that these may be related. The quantification of sediment transport in areas with no clusters, compared to the sediment transport in areas with high proportions of clustering, indicates that there is typically less entrainment from areas with more clustering.

Particles entering clusters most commonly enter from directly upstream of the cluster, however more than 20% of particle movements approach from a direction greater than 20° from the streamwise direction. Approximately 25% of all particle movements were associated with the formation or disintegration of a cluster and approximately 35% of particle movements bypassed a cluster.

Experimentation with various sediment grading compositions indicates that bimodal sediment forms clusters more readily. Higher proportions of sand changed the nature of particle
interactions by allowing particles to embed and slide more easily. These experiments also indicated that the presence of intermediate sized particles is also necessary for the formation of stoss and wake zones.
Chapter 8. Summary and Recommendations

A new application of photogrammetry has been successfully developed. The study of gravel dynamics using coloured particles, coupled with image analysis, has enabled in-depth observation of sediment transport and cluster development. This study bridges a gap between research into clusters conducted in the field and that conducted under idealised conditions in the laboratory. The photogrammetry technique that was developed in this study allows detailed study into sediment mechanics, similar to that of the idealised laboratory studies, but under more realistic conditions, due to the use of a graded gravel bed.

The use of painted gravel in the study enabled the development of a digital particle tracking program (DPT) that successfully tracked larger sediment (>9 mm) with high accuracy at a relatively low frame rate (0.75 fps). Smaller particles (>2 mm) were also successfully tracked at a much higher frame rate (30 fps). To the author’s knowledge, the level of accuracy attained in this tracking program has not been achieved by any previous studies attempting to observe the motion of individual particles in a moving gravel bed. During this study, the following attributes of the experimental set up were determined to be important in the success of any image analysis process:

- High image resolution that was appropriate to the observed subject
- Appropriate frame rate suitable for capturing particle movement
- Enough contrast to distinguish between entrained particles and the stationary bed, which in this case was achieved by the use of different coloured particles
- Consistent, bright lighting
- A stationary camera (and test section) to maintain a constant frame of reference

A number of experiments were conducted using a physical model in the Fluid Mechanics Laboratory in the Civil and Environmental Engineering Department at the University of Auckland. An initially screeded, graded gravel bed was observed continuously over a number of hours with the aim of studying the formation of clusters. The application of photogrammetry to the study of graded gravels as they are water-worked has highlighted a number of interesting phenomena.

The DPT program was applied to high and low frame rate footage of an individual experiment. This revealed large spatial and temporal variation of sediment transport rates.
Chapter 8. Summary and Recommendations

Investigation of transport patterns indicated that 30% of particle movements were entrained in localised events, that the fractional transport rate of the smaller size fractions was dependent on the transport rate and percentage of that size fraction available on the bed surface, and that larger fractions showed diminishing transport rates.

Image and statistical analysis was applied to the surface sediment to investigate the effects of armouring. At the higher flow rates, the bed was near to the critical armoured condition. The median grain size of the critically armoured surface was similar to the predicted value, verifying the equation proposed by Chin (1985). The presence of a large anchor stone on the surface of the bed caused the surface to adapt, ultimately reducing the protrusion of the stone, and resulting in a surface of similar complexity to that of a plain armoured bed.

Objective cluster identification was achieved by monitoring the stationary areas of the bed, and designating clusters as areas with stable groups of large particles. This tool was used in combination with DPT to obtain new insights into cluster formation. Cluster formation is an integral part of the armouring process. The formation of clusters was difficult to predict, while most large particles readily formed a wake, cluster formation was often dependent on the serendipitous deposition of a stone into the stoss of the anchor stone. Overall, during formation of the armour layer, clusters covered the surface progressively, generally initiating at the upstream end of the test section and forming further downstream over time. Higher flow rates result in a higher presence of clusters on the bed surface and a maximum surface coverage of around 34% was observed. Particle shape plays a role in cluster formation, where elongate stones form more stable clusters.

Clustering is enhanced by the presence of a stationary object on the bed. Whether this is in the form of the side wall, or an anchor stone placed on the central bed, a point of stability on the bed encourages the surrounding bed to stabilise. Because of their influence on the surrounding shear velocity, the relative size and frequency of these points of stability changes their effect on the surrounding bed. For example, if a stone is too large or if there are too many other anchor stones nearby, the surrounding shear velocity is increased and can negatively affect the stability of the surrounding bed.

This study indicated that clusters play a role in attenuating the transport of the surrounding bed. Study of the entrainment of particles surrounding a large, robust cluster indicated that peak transport rates were reduced, and average transport rates were less than they might have
been otherwise. Because the sediment transport rate inherently decreases as the experiment progresses, it is difficult to isolate the influence of clusters on the transport rate. By normalising the local entrainment rate with the spatial average entrainment rate of the bed, and normalising the local proportion of clusters present with the proportion of clusters covering the test section, the effect of clustering on sediment entrainment rates was assessed. A survey of every cluster from all experiments in this study showed that areas with a high degree of clustering reduced the amount of local entrainment, indicating that a high degree of clustering reduces entrainment from beyond the boundaries of the immediate cluster.

In the pursuit of a complete study into the formation and disintegration of clusters, it was necessary to delve into a new application for photogrammetry and also touch on aspects of sediment transport and gravel bed armouring. The relationships between clusters and the surrounding bed are complex, and further work remains to define the mechanics of this phenomenon. Therefore, recommendations for future research into clusters and other aspects of this study are:

I. The information gained from the photogrammetry process would be greatly enhanced with the use of stereo-photogrammetry. If a reliable stereo-photogrammetry set-up could be achieved, the 3D topographic information would enable continuous monitoring of peaks and troughs on the test section. This would be of great benefit to the identification of clusters, because a criterion for the identification of a cluster is that it protrudes, and height was impossible to measure using the 2D information obtained through photogrammetry. Stereo-photogrammetry would also enhance monitoring of the effect that clusters have on the surrounding bed, by enabling identification of changes in topography in areas without clusters.

II. Experiments from this study indicated some interesting trends, and further study into the effect of the addition of an anchor stone to the surface and of anchor stone shape is recommended. Additionally, more varied flow and sediment conditions would give an understanding of cluster behaviour. In particular, bimodal sediment beds should be investigated further, with the aim of replicating the clusters pictured in Chin (1985)’s work.

III. Clusters were formed on a static bed in this study. To replicate more extensive natural environments and enable comparison with a wider variety of other published work it
is recommended that experiments are also conducted on a dynamic bed. The use of painted gravels limits the availability of gravel to be used without significantly increasing the preparation time, but recirculation of the entrained sediment would alleviate this problem to some extent.

IV. Collection of flow information was omitted in this study due to the technical issue of maintaining photogrammetry whilst recording flow velocities. If this could be overcome, the addition of flow information to the wealth of information provided by photogrammetry would be useful.

V. The tracking program in this study was tailored to the observation of clusters and therefore optimised the tracking of larger particles. The development of the tracking program for the application to tracking smaller particles was given less emphasis. The ability to unobtrusively track sediment is an exciting prospect, and if developed further, could be a useful tool to help provide insight into other studies in addition to the formation of clusters.
## Appendix I. Experiment Summary

<table>
<thead>
<tr>
<th>Description</th>
<th>Code</th>
<th>Duration (min)</th>
<th>$Q$ (l/s)</th>
<th>$V_{av}$ (m/s)</th>
<th>$u^*$ (m/s)</th>
<th>DS profile</th>
<th>Velocity profile position relative to upstream end of test section (mm)</th>
<th>gap in data (min)</th>
<th>notes</th>
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<td>60</td>
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<td></td>
</tr>
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<td>66</td>
<td>0.92</td>
<td>0.075</td>
<td>y</td>
<td>-1000</td>
<td></td>
<td>Armour did not form, bed washed out</td>
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<tr>
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<td>A0G1Q66R1</td>
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<td>66</td>
<td>0.84</td>
<td>0.072</td>
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<td>90</td>
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<td>90</td>
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<td>n\a</td>
<td>900</td>
<td></td>
<td></td>
</tr>
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<td>330</td>
<td>66</td>
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<td>y</td>
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<tr>
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<td>72</td>
<td>0.87</td>
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<td>0.088</td>
<td>n\a</td>
<td>900</td>
<td>35</td>
<td>Ran out of battery</td>
</tr>
<tr>
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<td>A1G1Q72R2</td>
<td>341</td>
<td>72</td>
<td>1.02</td>
<td>0.087</td>
<td>n\a</td>
<td>900</td>
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<td>A1G1Q72R3</td>
<td>360</td>
<td>72</td>
<td>1.02</td>
<td>0.085</td>
<td>n\a</td>
<td>900</td>
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<td>0.99</td>
<td>0.084</td>
<td>y</td>
<td>900</td>
<td>20</td>
<td>Excellent cluster formed, ran out of battery</td>
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## Appendix I. Experiment Summary

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<tr>
<th>Description</th>
<th>Code</th>
<th>Duration (min)</th>
<th>$Q$ (l/s)</th>
<th>$V_{av}$ (m/s)</th>
<th>$u^*$ (m/s)</th>
<th>DS profile</th>
<th>Velocity profile position relative to upstream end of test section (mm)</th>
<th>Notes</th>
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<td>Bimodal D50 1mm</td>
<td>A0G2Q66</td>
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<td></td>
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<td>66</td>
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<td>A1G4Q72</td>
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<td>339</td>
<td>66</td>
<td>0.85</td>
<td>0.074</td>
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<td>Not included: Camera vibrations</td>
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<td></td>
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<td>y</td>
<td>-1000</td>
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<td>Repeat 1 Anchor stone (med)</td>
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<td>0.074</td>
<td>y</td>
<td>-1000</td>
<td></td>
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<td>0.90</td>
<td>0.074</td>
<td>y</td>
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<td>A1G3Qv</td>
<td>117</td>
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<td>-1000</td>
<td>-1000</td>
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<td>Bimodal D80 1mm</td>
<td>A1G3Q66</td>
<td>118</td>
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<td>0.85</td>
<td>0.072</td>
<td>y</td>
<td>-1000</td>
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<td>251</td>
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<td>0.084</td>
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<td>-1000</td>
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<td>-</td>
<td>n/a</td>
<td>900</td>
<td>Not included</td>
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</table>

Table AI-1 Notated experiment summary, including experiments that were not analysed (shaded grey) and the reasons why they were excluded.
Appendix II. Velocity Profiles

Figure AII-1 Logarithmic velocity profiles along the length of the flume, distances with reference to the upstream edge of the test section
Appendix II. Velocity Profiles

Figure AII-2 Velocity profiles of A0G1 and A1G1 type experiments
Figure AII-3 Velocity Profiles of A4GI and M4GI type experiments
Figure AII-4 Velocity profiles of G2, G3 and G4 type experiments
Appendix III. Sediment Grading

| sieve size (mm) | Chin (1985)-Mixture 4 | | | Chin (1985)-Mixture 3 | | |
|-----------------|-----------------------|-----------------|------------------|---------------------|------------------|
|                 | G1 Cumulative Frequency (%) | G2 Cumulative Frequency (%) | G3 Cumulative Frequency (%) | G4 Cumulative Frequency (%) |
| 27              | 100                   | 100             | 100              | 100                 |
| 25              | 98                    | 98.8            | 98.6             | 99.5                |
| 9.5             | 80                    | 87.8            | 84.7             | 94.8                |
| 4.75            | 55                    | 71.5            | 84.7             | 87.9                |
| 2.8             | 36                    | 54.7            | 84.7             | 80.9                |
| 1.204           | 12.5                  | 51.5            | 80.7             | 79.5                |
| 0.3             | 0                     | 0.07            | 0.09             | 0.02                |
| 0.1             | 0                     | 0               | 0                | 0                   |

Table A2-1 Data summary of original grain size distributions

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<th>$D_{av}$ (mm)</th>
<th>Frequency ($F_i$)</th>
<th>Cum Freq (%)</th>
<th>$F_iD_{av}$/sum</th>
<th>Frequency (%)</th>
<th>Cumulative Frequency (%)</th>
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<td>25</td>
<td>26</td>
<td>2</td>
<td>98</td>
<td>52</td>
<td>7.7</td>
<td>92.2</td>
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<tr>
<td>9.5</td>
<td>17.25</td>
<td>18</td>
<td>80</td>
<td>310</td>
<td>46.4</td>
<td>45.7</td>
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<td>7.125</td>
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<td>55</td>
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<td>55</td>
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<tr>
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<td>sum</td>
<td>668.1</td>
<td></td>
<td>sum</td>
<td>5</td>
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</tr>
</tbody>
</table>

Table AIII-1 Conversion of a volumetric (subsurface) sample to an areal (surface) sample, using $G1$ grain size distribution and calibration coefficient obtained from Kellerhal and Bray (1971)
Appendix III. Sediment Grading

Figure AIII-1 Evolution of the surface grain size distribution of each A0G1 experiment over time, including the subsurface sieved grain size distribution and the calibrated subsurface grain size distribution.
Appendix III. Sediment Grading

Figure AIII-2 Evolution of the surface grain size distribution of each A1G1 and A4G1 experiment over time, including the subsurface sieved grain size distribution and the calibrated subsurface grain size distribution.
Figure AIII-3 Evolution of the surface grain size distribution of each MA4G1, G2, G3 and G4 experiment over time, including the subsurface sieved grain size distribution and the calibrated subsurface grain size distribution.
Appendix IV. Cluster Formation and Sediment Entrainment Rate

This section contains the record of areal aggregate sediment entrainment rate, percentage surface coverage of clusters and depth of erosion over time. Experiments A0G1Q72 R2, A1G1Q72R1, A0G3Q66, and A1G4Q72 have been excluded due to problems with the image identification process (either technical difficulties or wash out). As the cluster identification process is reliant on a continuous photographic record, in experiments were a gap in data collection was encountered, the cluster identification was affected. This translates to drastic drops in the proportion of surface coverage with clusters. Experiments with data gaps can be identified using the annotated experiment summary.

![Graph showing data on cluster coverage, depth of erosion, and erosion rate.]

Figure AIV-1 Areal aggregate sediment entrainment rate, depth of erosion and cluster surface coverage for A0G1Q60 and corresponding repeated experiments
Figure AIV-2 Areal aggregate sediment entrainment rate, depth of erosion and cluster surface coverage for A0G1Q66 and corresponding repeated experiments
Figure AIV-3 Areal aggregate sediment entrainment rate, depth of erosion and cluster surface coverage for A0G1Q72 and corresponding repeated experiments.
Figure AIV-4 Areal aggregate sediment entrainment rate, depth of erosion and cluster surface coverage for A1G1Q72 and corresponding repeated experiments.
Figure AIV-5 Areal aggregate sediment entrainment rate, depth of erosion and cluster surface coverage for A1G1Q66, A4G1Q66 and A4G1Q72
Figure AIV-6 Areal aggregate sediment entrainment rate, depth of erosion and cluster surface coverage for MA4G1Q66 and MA4G1Q72
Figure AIV-7 Areal aggregate sediment entrainment rate, depth of erosion and cluster surface coverage for A0G2Q66 and A1G4 experiments
Figure AV-1 Particle track record for each experiment, showing the streak line of each particle movement, with time scale indicated by colour for A0G1Q66 and corresponding repeated experiments.
Figure AV-2 Particle track record for each experiment, showing the streak line of each particle movement, with time scale indicated by colour for A1G1Q66, A0G1Q72 and corresponding repeated experiments.
Figure AV-3 Particle track record for each experiment, showing the streak line of each particle movement, with time scale indicated by colour for A1G1Q72, and corresponding repeated experiments.
Figure AV-4 Particle track record for each experiment, showing the streak line of each particle movement, with time scale indicated by colour for A4GI and MA4GI experiments.
Figure AV-5 Particle track record for each experiment, showing the streak line of each particle movement, with time scale indicated by colour for $A0G2$, $A0G3$ and $A1G4$ experiments.
Appendix VI. Cluster Position Development

Figure AVI-1 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A0G1Q60

Figure AVI-2 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A0G1Q66
Figure AVI-3 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A0GI66L2

Figure AVI-4 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A0GI72
Figure AVI-5 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A0G1Q72R1

Figure AVI-6 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A0G1Q72R3
Appendix VI. Cluster Position Development

Figure AVI-7 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment AIG1Q66

Figure AVI-8 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment AIG1Q72
Figure AVI-9 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A1G1Q72R1

Figure AVI-10 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A1G1Q72R2

Figure AVI-12 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A1G1Q72R3
Appendix VI. Cluster Position Development

Figure AVI-13 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A4G1Q66

Figure AVI-14 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A4G1Q72
Figure AVI-15 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment MA4GIQ66

Figure AVI-16 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment MA4GIQ72
Appendix VI. Cluster Position Development

Figure AVI-17 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A0G2Q66

Figure AVI-18 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A1G4Q50

Figure AVI-19 Cluster positions on the test section for at 10 minute intervals, where time progresses from left to right then top to bottom, experiment A1G4Q66
Appendix VII. Surface Elevation Plots

Figure AVII-1 Water-worked surface elevation plot, experiment A0GIQ60

Figure AVII-2 Water-worked surface elevation plot, experiment A0GIQ66
Appendix VII. Surface Elevation Plots

Figure AVII-3 Water-worked surface elevation plot, experiment A0G1Q72

Figure AVII-4 Water-worked surface elevation plot, experiment A1G1Q66

Figure AVII-5 Water-worked surface elevation plot, experiment A4G1Q72
Figure AVII-6 Water-worked surface elevation plot, experiment A4G1Q66

Figure AVII-7 Water-worked surface elevation plot, experiment A4G1Q72

Figure AVII-8 Water-worked surface elevation plot, experiment MA4G1Q66
Appendix VII. Surface Elevation Plots

Figure AVII-9 Water-worked surface elevation plot, experiment MA4G1Q72

Figure AVII-10 Water-worked surface elevation plot, experiment A0G2Q66

Figure AVII-11 Water-worked surface elevation plot, experiment A0G3Q66
Appendix VII. Surface Elevation Plots

Figure AVII-12 Water-worked surface elevation plot, experiment A1G4Q50

Figure AVII-13 Water-worked surface elevation plot, experiment A1G4Q66

Figure AVII-14 Water-worked surface elevation plot, experiment A1G4Q72
Appendix VIII. Guide to Appendix VIII-D

This appendix provides a summary of the information stored in the additional DVD, Appendix VIII-D. This appendix is provided as a case study, where experiment $A1G1Q66$ is presented to demonstrate the cluster identification process. Three videos in .FLV format are included, where all three show a different aspect of the cluster identification process. The third video also includes the results of the DTP.

<table>
<thead>
<tr>
<th>Video Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Video 1-Cluster ID 1 Image Erosion.flv</strong></td>
<td>Sequential erosion of image $I_i$, subtracting the subsequent 250 frames (0.067 fps). Playback speed = real time x40</td>
</tr>
<tr>
<td><strong>Video 2-Cluster ID 2 Eroded Images Sequence.flv</strong></td>
<td>Sequence of images having undergone 150 frame image erosion. One image every 300 frames (0.0022fps) for the experiment duration. Playback speed = real time x600</td>
</tr>
<tr>
<td><strong>Video 3-DPT Cluster ID.flv</strong></td>
<td>Particle tracks and identified clusters overlaid onto the photographic record of experiment $A1G1Q66$ (0.67fps). Playback speed = real time x10</td>
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References


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